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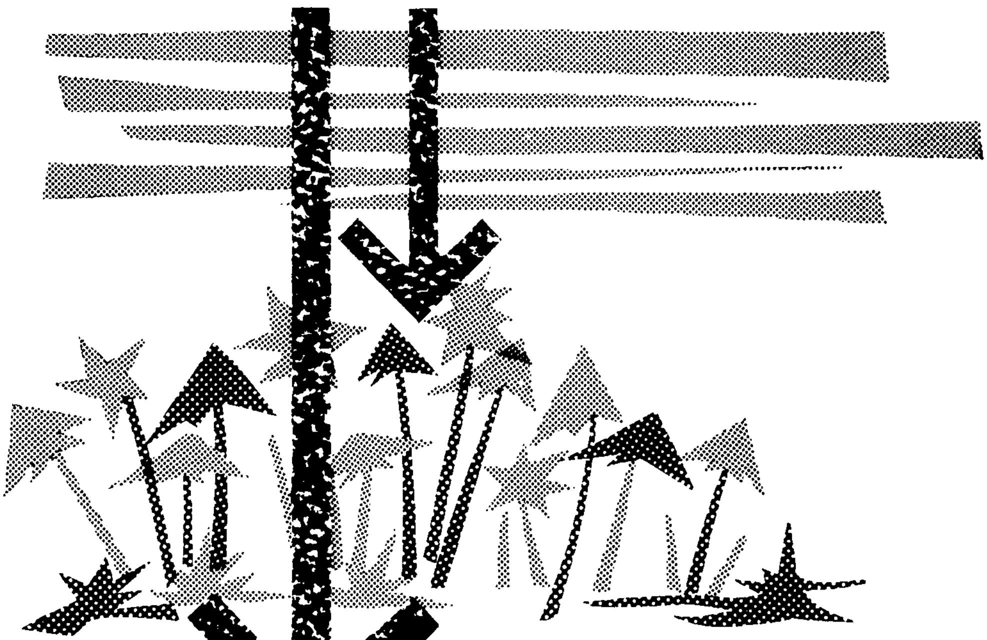
JUNGLE CANOPY PENETRATION



VOLUME 1
DIFFUSION MEASUREMENTS

Bendix SYSTEMS DIVISION OF THE BENDIX CORPORATION

BSC 36174 -

JUNGLE CANOPY PENETRATION
(U)

FINAL REPORT

VOLUME I

DIFFUSION MEASUREMENTS

PREPARED FOR

THE DEPARTMENT OF THE ARMY

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ACKNOWLEDGEMENT

The Bendix Corporation gratefully acknowledges the cooperation and courtesies extended by the government of the Republic of Colombia during the Jungle Canopy Program. The operation of a program of this nature in a foreign country without the enthusiastic assistance from the government of that country would present insurmountable difficulties.

By working through the United States Department of State, the United States Embassy in Bogota, and the Inter-American Geodetic Survey with headquarters in Ft. Clayton, Canal Zone, arrangements were made with the Augustin Codazzi Instituto Geografico of Bogota, Colombia to allow the project to enter Colombia under an existing agreement between the United States government and the government of Colombia covering the survey work being done by the Inter-American Geodetic Survey.

Without this cooperation and the subsequent assistance rendered by Mr. James Haahr, the American Consul in Medellin, the Maderas del Darien Ltda., and the gratuitous assistance from numerous Colombians in Medellin, Turbo and Chigorodo the successful completion of the project would have been impossible.

It is appropriate to acknowledge those who participated in the several phases of the program. Workers in the field included Harold W. Baynton, Alan L. Cole, Gerald C. Gill, George J. Leszczynski, James W. Mair, Reinhardt Mittlestadt, Allan Ramrus, and G. H. Spence. In addition to these, W. Gale Biggs, Fred W. Brock, E. Wendell Hewson and Paul E. Sherr made major contributions to the data analysis and interpretation.

PREFACE

The Jungle Penetration program was conducted primarily to describe and define the ventilation processes of the rainforest. As a means to this end an aerosol tracer technique was used. Fluorescent zinc cadmium sulfide, which approximates a true aerosol, was released above the forest and its concentration above and below the canopy measured during the succeeding hours.

In order that the nature of the ventilation might be fully understood and that a basis might exist for extrapolating the results to other forests, two relevant but subsidiary data collections were also performed. First, the site of the ventilation experiments was instrumented with meteorological sensors which were used to collect data during the experiments. Secondly, a complete survey was made of the vegetation in the immediate vicinity of the test site.

The final report has been prepared in three volumes to permit the specialized reader to find what interests him without reading the complete report. This first volume, entitled "Diffusion Measurements," describes the principal findings of the fluorescent particle experiments, and presents a mathematical model of diffusion through the rainforest. Volume II, "Vegetation and Meteorological Studies," contains the complete report of the vegetation survey and a description of the climatology of the test site based on the collection of meteorological data. Volume III, "Logistics, Instrumentation, and Data Processing," is essentially the account of how the data reported In Volumes I and II were acquired.

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SECTION 1

INTRODUCTION AND STATEMENT OF OBJECTIVES

This program was conceived and planned as an investigation of the ventilation processes of a tropical rainforest. A convenient and proven technique for such an investigation involves the release of an aerosol tracer above the forest. The ventilation of the forest is then measured in terms of the extent to which the tracer penetrates the canopy, and moves horizontally within the forest.

Penetration of the canopy and lateral movement within the forest by an aerosol are influenced both by the forest and by meteorology. Since the forest is in a sense a parameter, a complete description of the vegetation is essential to extrapolating the results to other sites. The importance of meteorology in diffusion clearly requires the collection of meteorological data.

Zinc cadmium sulfide, which fluoresces under ultraviolet light, was selected as the tracer. The experimental design was based on a series of field trials to develop information in the following four categories.

1. The diffusion processes in the region just above and below the vegetative canopy

2. The distribution of tracer material below the canopy as a function of height

3. The rate and direction of below-canopy aerosol projection relative to that above canopy

4. The relating of these diffusion rates to measurable meteorological and physical parameters via suitable diffusion models.

In addition, to the extent that the data might illuminate other facets of diffusion, all possible inferences and conclusions should be drawn from

the study. These determinations were to be made with respect to a uniform jungle canopy that was devoid of holes and that covered flat land well removed from the influence of hills and valleys.

In selecting the various meteorological sensors and tracer samplers, in choosing sensor locations in all the details of experimental design, there was recognition that this was a problem of diffusion, and that meteorology would, in some way, assume a deterministic role. In arriving at a test plan, one possible approach is to develop, from theoretical considerations, a model of the diffusion processes and to tailor the experimental design to provide a series of tests of the theoretical model. If the model should prove to be valid, the choice of an optimized design favors rapid analysis of the data along predetermined lines and the experiment is likely to be the definitive work on the subject. On the other hand if the model should prove to be invalid, there is a risk that there has been no collection of the data needed to establish the true nature of the processes. Another field program may then be required. The alternative approach is to develop a more generalized design that assures the collection of substantial quantities of meteorological and tracer data, the analysis of which will establish the nature of the processes at work. Even if the processes are unexpected, the broad scope of the design assures that their general nature will become evident and explainable. Once a model has been determined from experimental evidence, it is a simple matter to optimize the design in order to refine and extend our understanding in future studies.

The decision was to use the latter approach. The experimental data then assume a position of great importance since they must be so processed as to reveal the nature of penetration and diffusion. This philosophy of design, in turn, determines the method of presentation of material in the final report. Section 2 contains a condensed account of the experimental design and is limited to what is essential to an understanding of the later sections. The analyzed data are then presented at some length in Section 3 in various tables and graphs which, in turn, become the basis of first, a qualitative exposition of the penetration processes, followed by a mathematical modeling of the processes. With the processes defined, recommendations for improving the experimental design are then offered.

Volume I contains a complete account of the diffusion experiments and can be read and understood without reference to the other volumes. Details concerning the vegetation and microclimatology of the site appear in Volume II, and the complete account of logistics and instrumentation appears in Volume III.

SECTION 2

EXPERIMENTAL DESIGN

The design of an experiment to achieve the objectives outlined in Section I from site selection through field procedures, is described in this section. The main features that are presented here have been extracted from a more complete account appearing in Volume III of this report.

2.1 SITE SELECTION

A number of criteria were established for the site in order to eliminate uncontrollable variables. Level terrain was wanted in order to avoid the complications which might be introduced by slope winds or drainage effects. Rivers, lakes, swamps, and artificial holes in the jungle canopy were to be avoided so that penetration of the canopy might be the only way for the tracer material to reach ground. Two climatological criteria were also important. The first of these concerned wind direction. The test plan provided for a line of samplers to be installed parallel to the prevailing wind. A persistant prevailing wind was therefore needed to provide ample test opportunities. The second climatological criterion was that there should be a dry season of at least three months since it was required to conduct the penetration trials in the absence of rain. Finally, the area selected had to be such that the field party could complete their mission without devoting a major portion of the effort to subsistence and logistics problems.

The area selected for the study was in northwestern Colombia. Figure 2-1 shows the location of the site 20 miles south of the Gulf of Uraba. Access was via the Rio León from Turbo, the nearest settlement with daily air service. Figure 2-2 is an aerial view of the Rio León near the site of these experiments. Figures 2-3, 2-4, and 2-5, views of the rain forest in this area, reveal the general flatness of the forest and the undulating nature of the canopy. The vegetation study* established that this was typical rainforest.

*A detailed study of the rain forest at the León site is presented in Part I, Volume II, of this report.

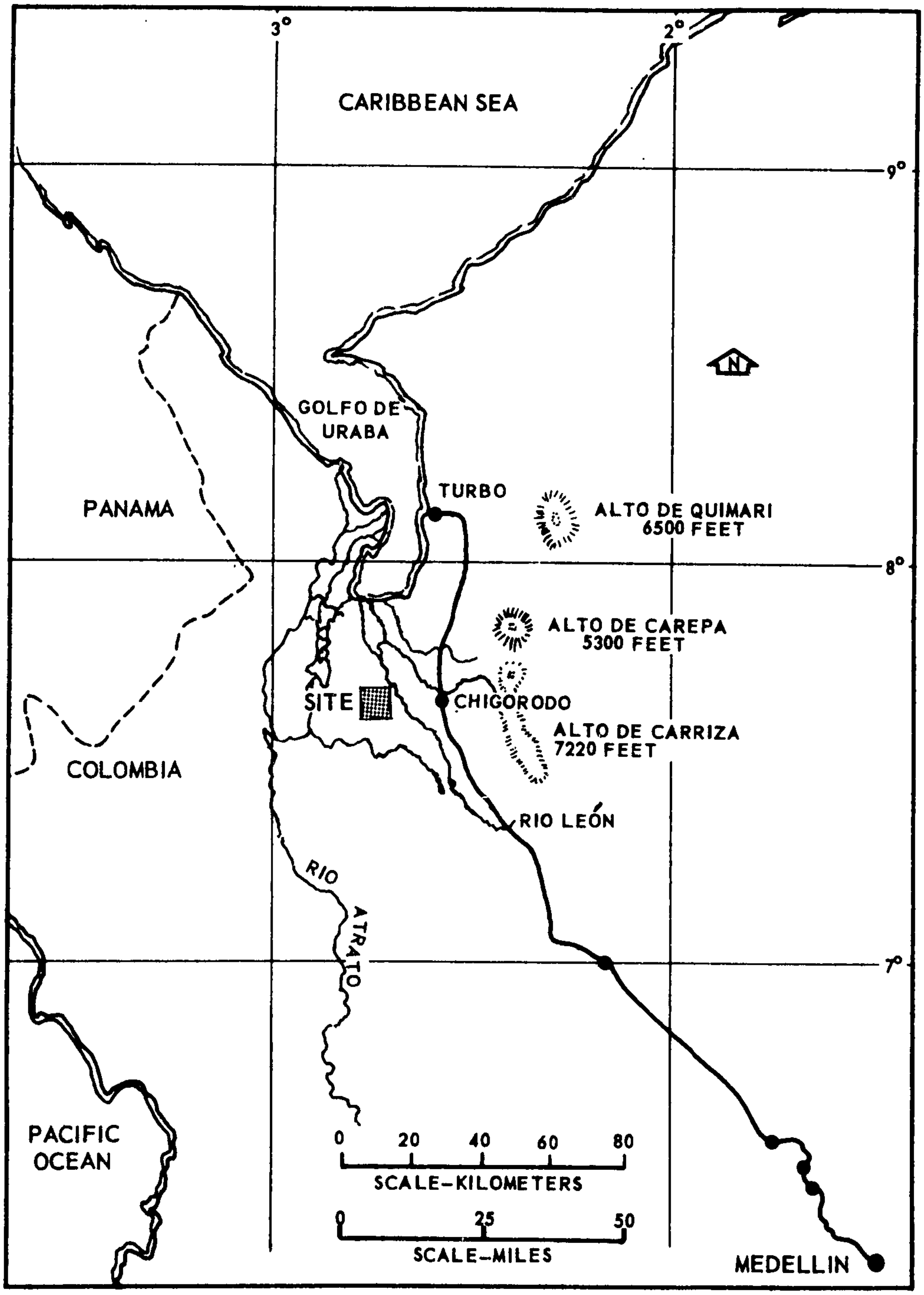

Figure 2-1Site for Jungle Canopy Penetration Study Chigorodo, Colombia

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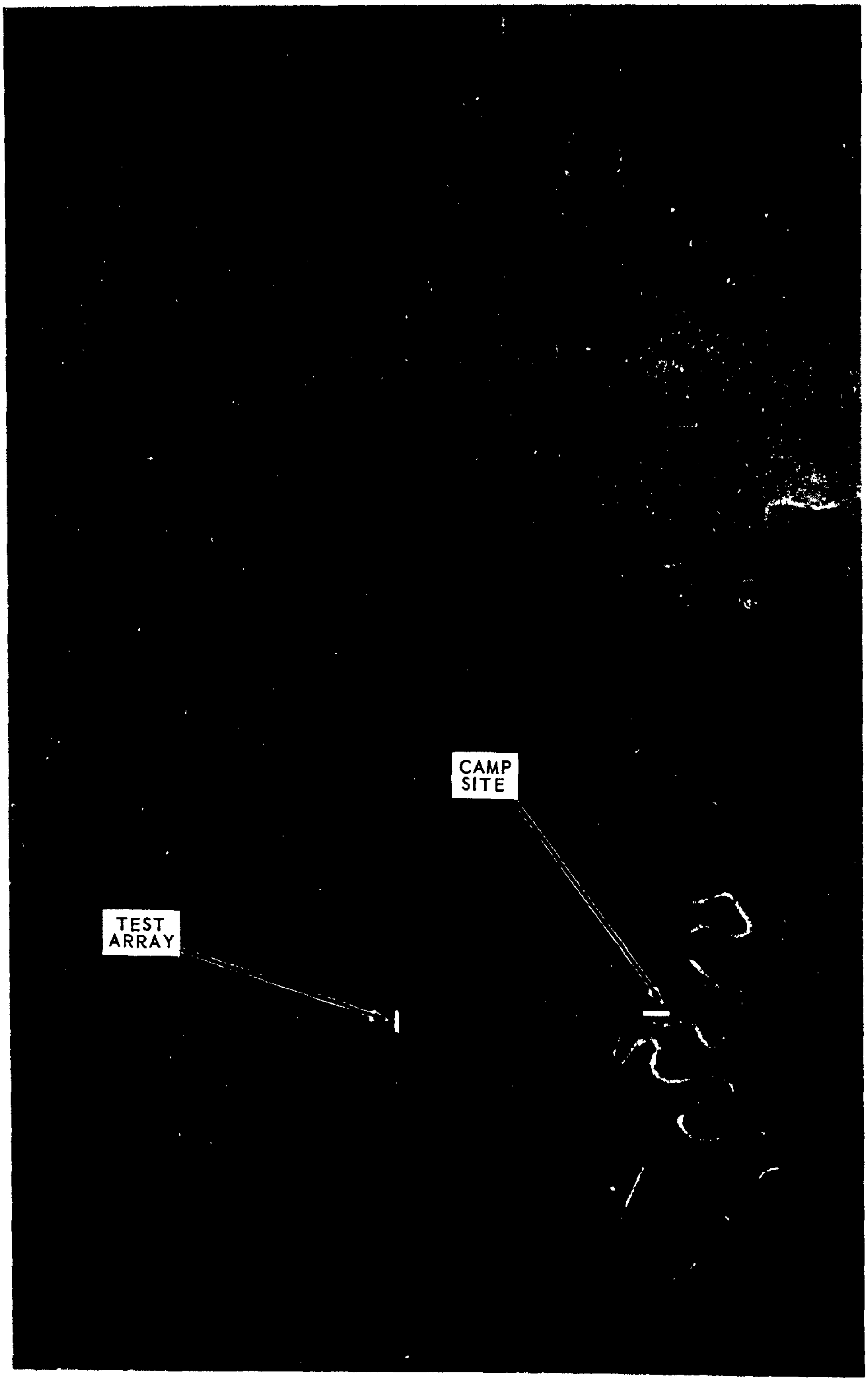


Figure 2-2 Aerial View of Forest Showing Rio León and Locations of Camp Site and Test Array

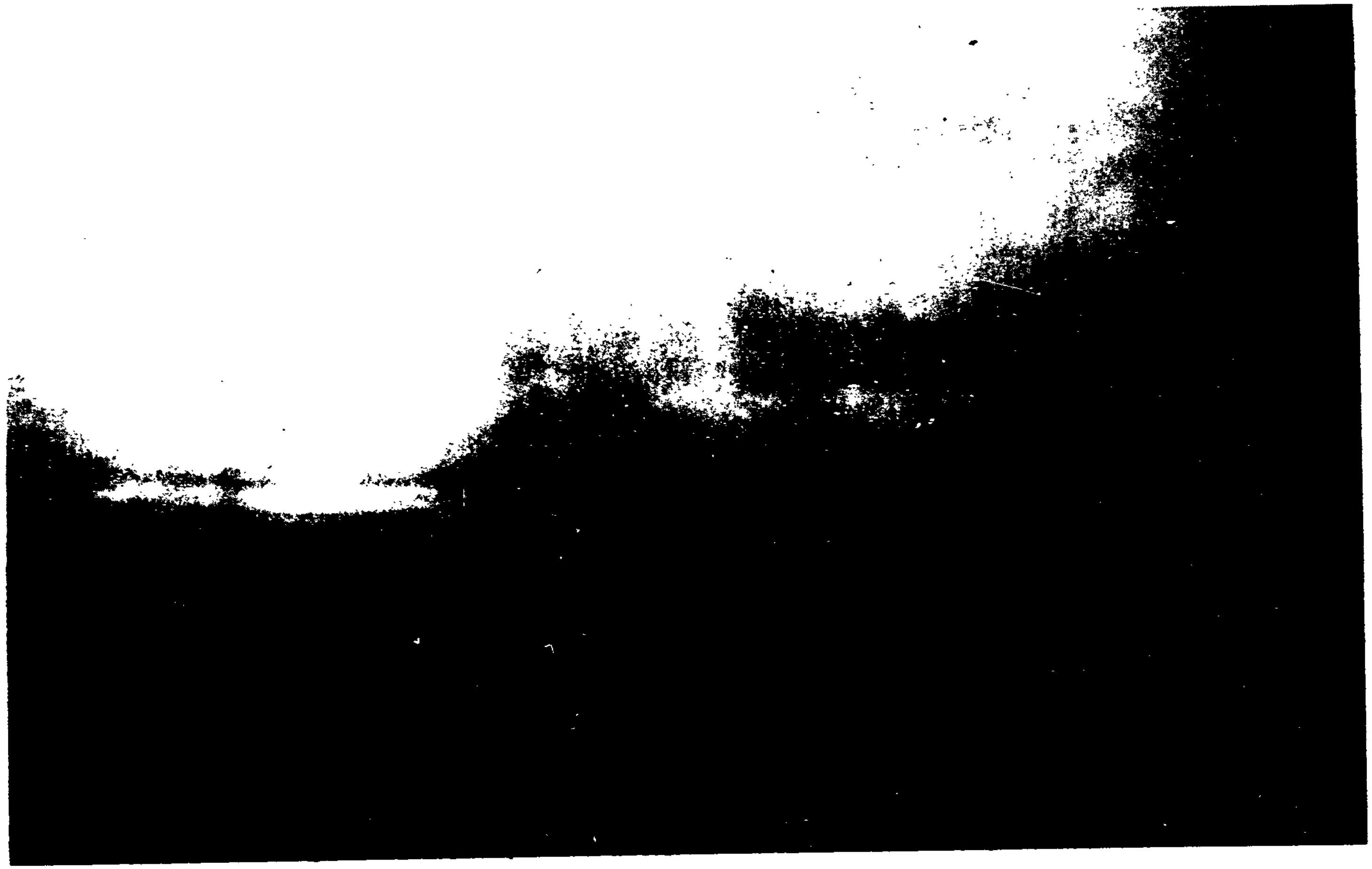


Figure 2-3 Tropical Rain Forest Looking South Near the Mouth of the León

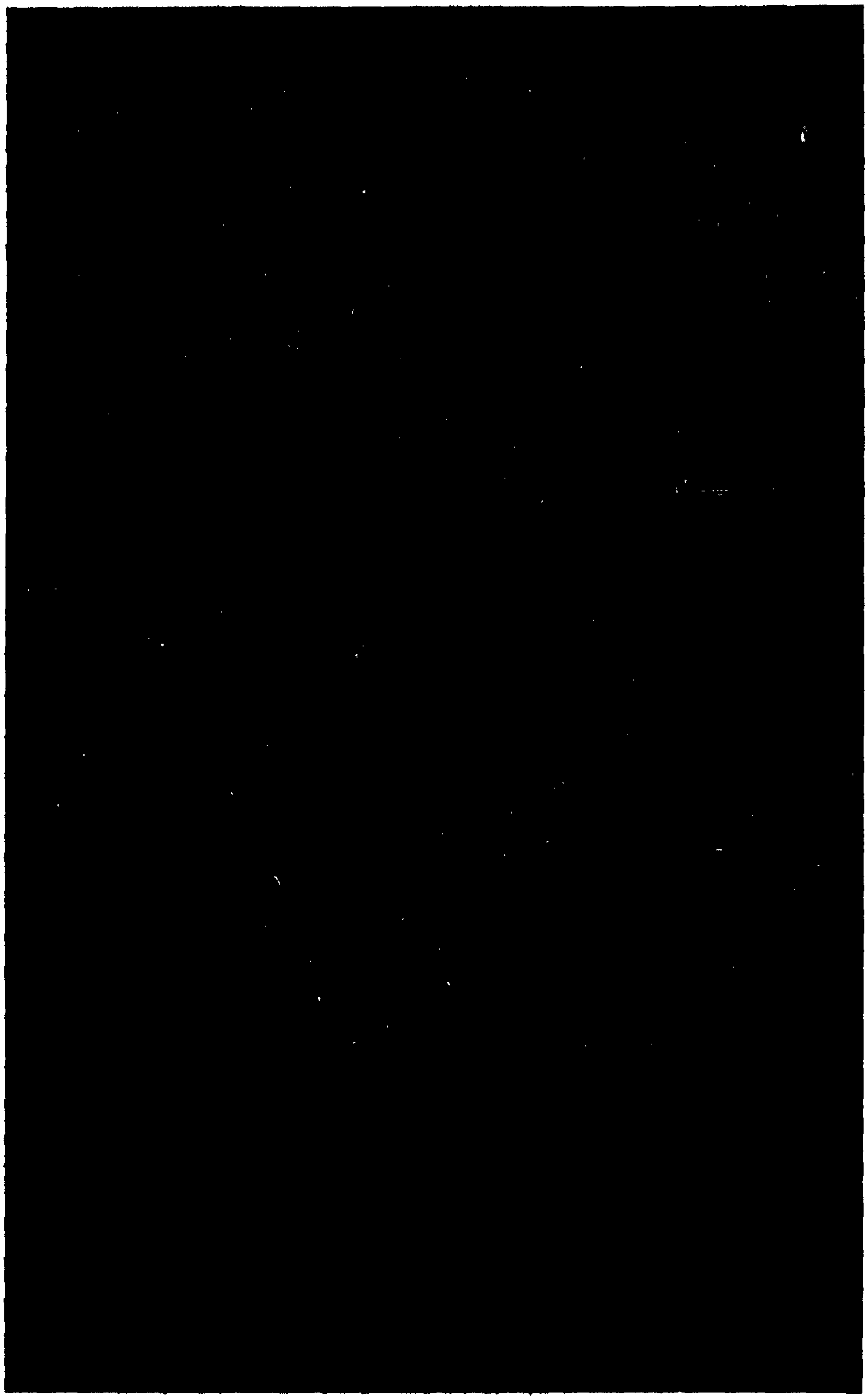


Figure 2-4 Tropical Rain Forest Between León and Atrato Rivers

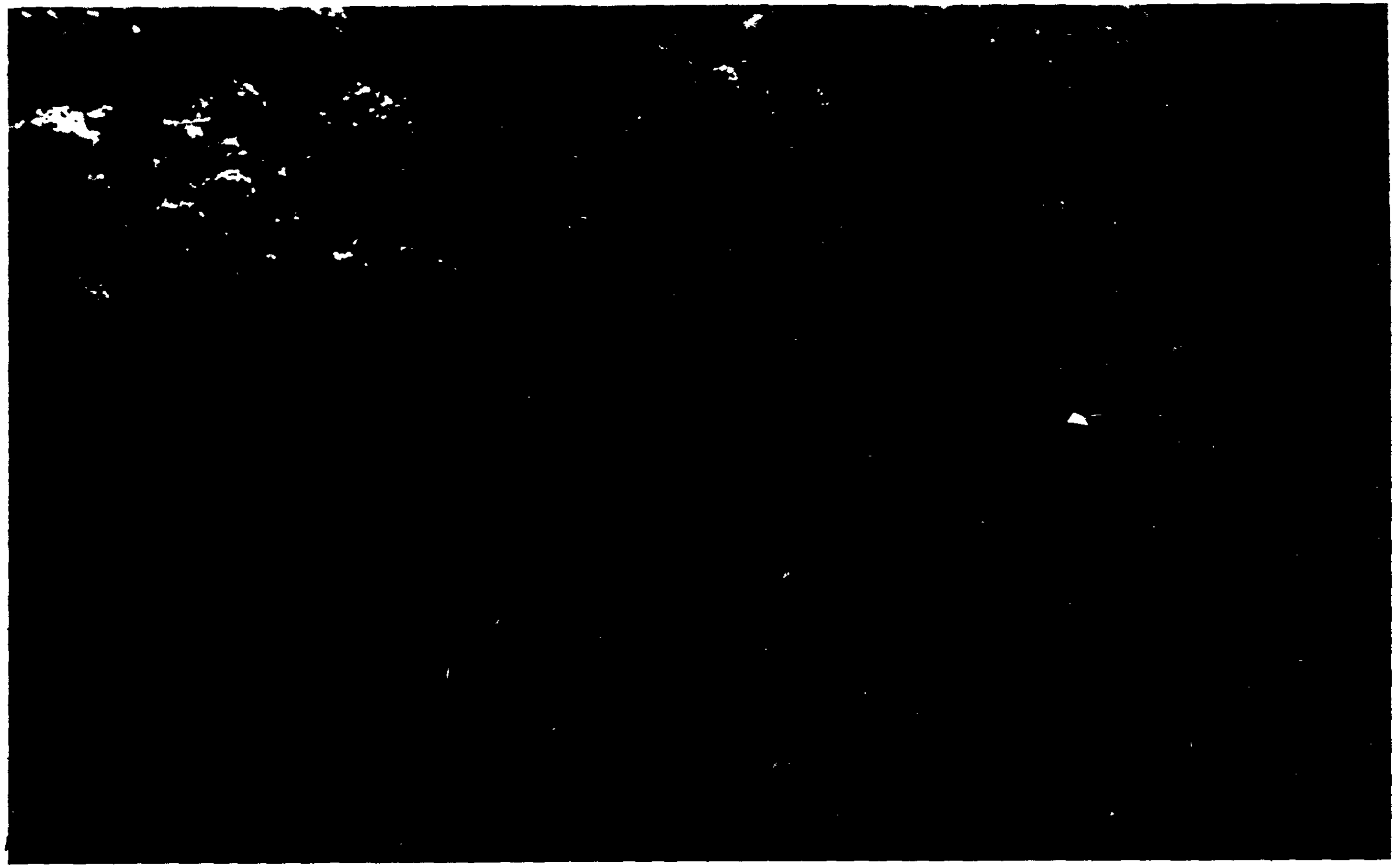


Figure 2-5 Tropical Rain Forest Between León and Atrato Rivers
(Close up view)

2.2 TEST PLAN

A formal test plan was developed early in the program. It called for field experiments to be conducted during the 1962 dry season (January, February, March) at a representative jungle site in Colombia. During these experiments, fluorescent tracer material (ZnCdS, identified henceforth as FP for fluorescent particle), was to be released at a known rate from an aircraft to provide an aerial crosswind line source upwind from a sampling array. This tracer is easy to detect, readily dispensed from aircraft, manufactured to a high degree of uniformity, is stable and safe and with its mass mean diameter of 2.5 microns, has a Stokes' settling speed of only 2.74 m/hr. Above and below the canopy formed by the crowns of the forest trees, mean half-hourly measurements of tracer concentrations were to be made and meteorological variables pertinent to the analysis of the diffusion of the tracer material were to be recorded.

The sampling array was to be arranged on a north-south line to coincide with the prevailing wind direction. A minimum of ten trials was required, eight during the night and two during the day. Six of the night trials and one of the day trials were to be conducted under clear skies (i.e., less than four-tenths cloud cover). The remaining three trials were to be conducted under cloudy skies. Additional trials were to be conducted if time permitted. For these trials, the Test Director was to select opportunities for the collection of useful data. Trials were to be conducted during rain-free periods with the wind from the north.

2.3 TEST CRITERIA

Included in the test plan was a rigorous statement of the meteorological criteria required for the conduct of penetration trials. These criteria, taken verbatim from the test plan, are as follows:

1. "A minimum of 10 successful trials is planned, 6 on clear nights, 2 on cloudy nights, 1 on a clear day, and 1 on a cloudy day. Conditions for additional trials will be selected by the test director to provide replicate data or to extend the range of meteorological test conditions.

2. "Success of a trial is characterized by: (a) no rain at the time of release of the FP, (b) less than 0.01 inches of rain up to five hours after release, but any rain after this time will not abort a trial, (c) wind speed at the 60 meter level $\overline{>}$ and $\overline{<}$ 35 miles per hour at release time, (d) wind direction such that fumigation

of the entire test complex is accomplished without edge effects as indicated by millipore filter counts above and below the canopy, (e) during the first 5 hours after release no winds more than plus or minus 90 degrees from north for periods greater than 15 minutes but any wind shift after 5 hours will not abort the test.

3. "The procedures detailed below will be followed unless field experience demonstrates that they are defective. A minimum of 3 shakedown trials is planned to establish the feasibility of the procedures and train the crew.

"It is intended that trials be conducted when the initial wind direction at 60 meters is within 30 degrees of the major axis of the array. If slightly greater tolerances prove necessary in order to complete the 10 tests, the director will arrange for appropriate compensation in the dissemination of the FP.

"At his discretion the test director can develop new plans whose merit becomes evident from field experience, but these plans must be consistent with the test objectives."

No deviations from test criteria were required during the test period except for the selection of clear and cloudy sky conditions. As is indicated in Section 5 of this report, tests were conducted over a sufficiently broad range of meteorological conditions to reveal the effects of meteorology.

2.4 INSTRUMENT ARRAY

The location of the test array with respect to the León River is shown in Figure 2-6. The geometry of the test array and location of the various sensors is indicated in Figure 2-7. Twelve sampling stations were placed nominally at 100 meter intervals along a north-south line. Two additional sampling stations, 13 and 14 of Section AA in the Figure, were located 200 meters east and west of the main sampling line, 500 meters from the north end of the array. Thus, the primary axis of the array was 1100 meters long and the secondary axis was 400 meters long. Two-hundred-foot guyed towers were erected at both ends of the primary axis. Figure 2-8 is a view of the north tower. At the intersection of the secondary axis with the primary axis, a 140-ft tower was erected to permit above-canopy sampling for FP

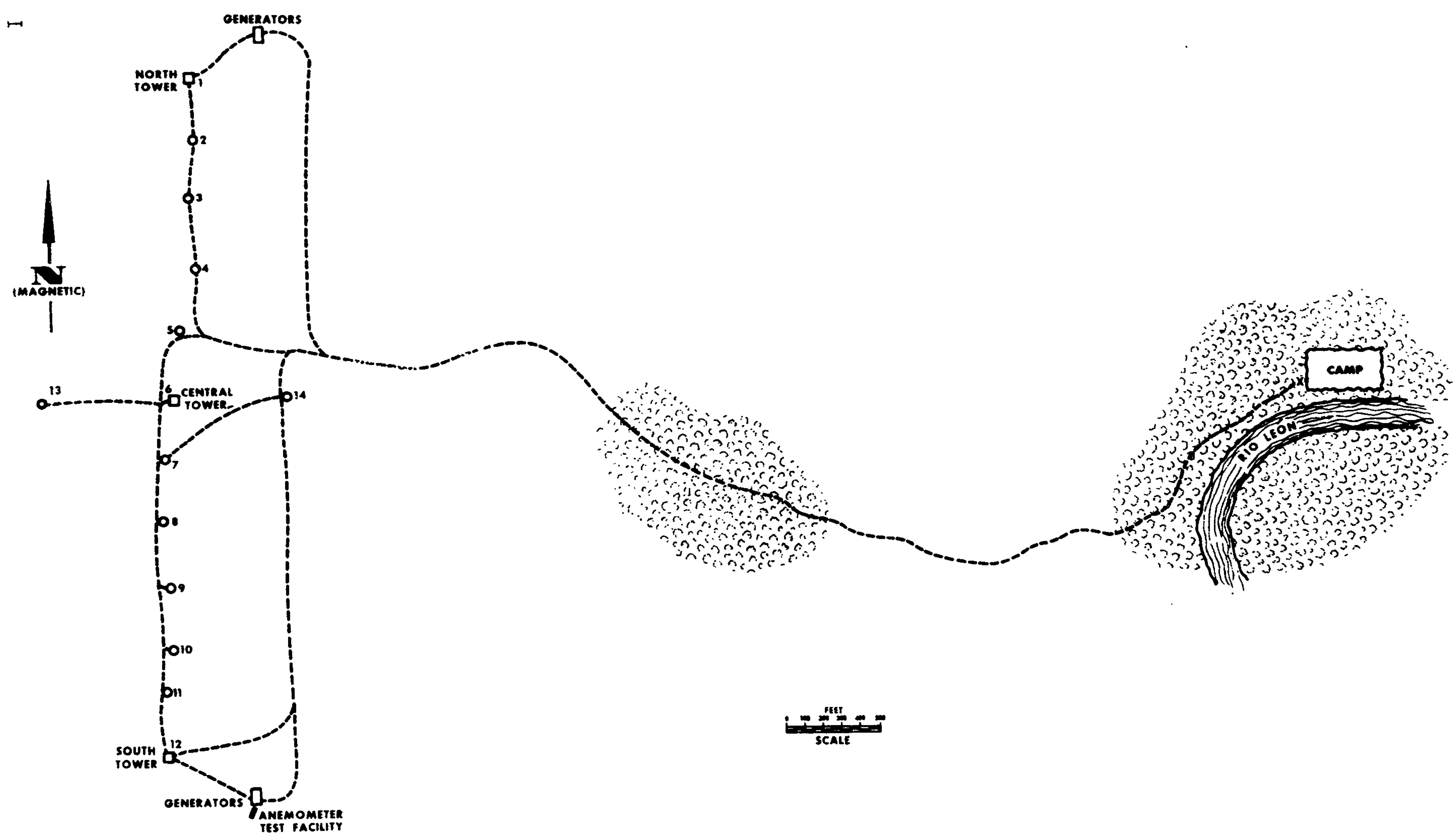


Figure 2-6 Surveyed Map of the Array in Relation to the Camp Site, to Scale

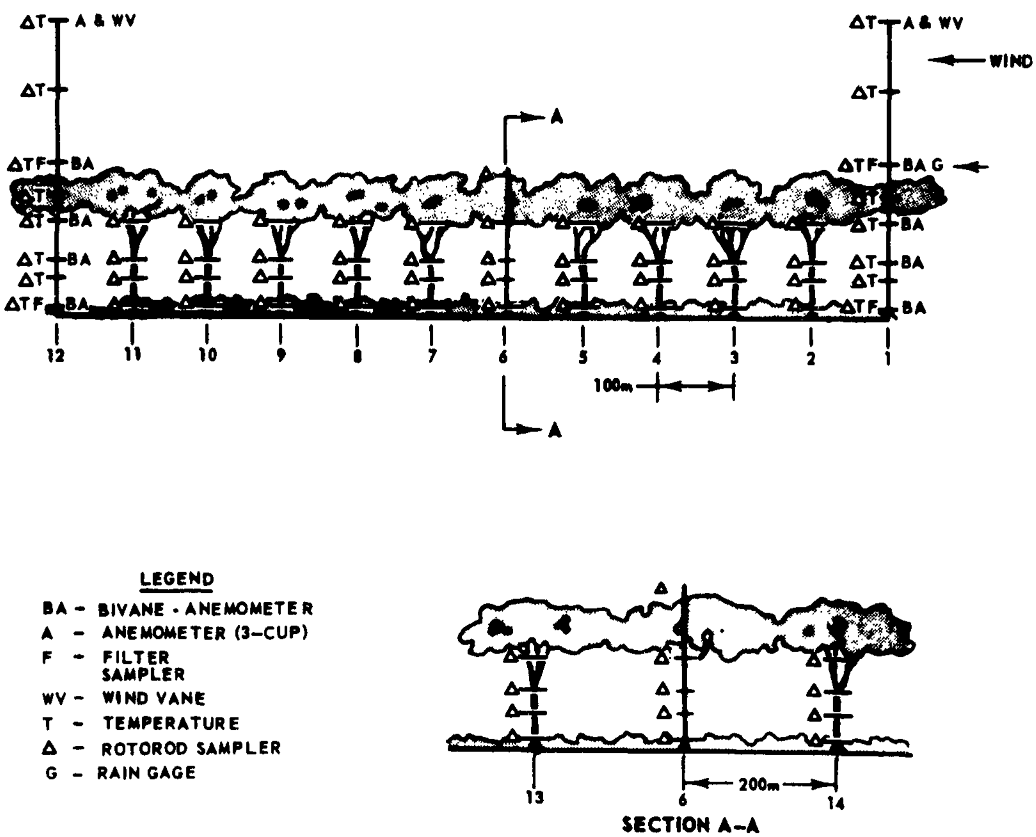


Figure 2-7 Test Array Used for Jungle Canopy Penetration Study

Figure 2-8 View of the North Tower as Erected in the Forest

Figure 2-9 Looking up the North Tower From 140 Feet

at an intermediate point. The towers at the extremities of the network supported both meteorological sensors and FP samplers. The meteorological sensors on each tower consisted of eight thermometers and four anemometer bivanes, installed at the levels indicated on Figure 2-7, and a vane and cup anemometer at the top of the tower. In addition, a tipping-bucket rain gage was attached to the north tower at about 150 ft. Figure 2-9, a view looking up the north tower from 140 feet, shows the top three temperature installations, a sequential sampler and pump, the rain gage, and the wooden cross-arm which supported the rotorods. Trees were used for the 11 other stations of the array. From these trees rotorod samplers were suspended from a cross-arm erected for that purpose.

After the towers were erected, the vegetation was surveyed to select appropriate heights for the various sensors. Figure 2-10 (based on a sketch drawn in the field) shows the height selected for each instrumentation level. It should be noticed that the openness depicted under the canopy in Figure 2-7 is not present. Photographs taken facing each of the cardinal points of the compass at each of the 8 instrumentation levels on the north tower (station 1) are shown in Figure 2-11. Similarly, Figure 2-12 shows views from the four levels at station 9, one of the trees. Figures 2-13 and 2-14 are typical views of the forest structure as it appears at ground level.

2.5 DISSEMINATION OF FP

The release of FP was by means of a standard airborne FP disseminator designed to discharge FP at a rate of about 3 lbs/mile at an airspeed of 150 mi/hr. The flight operations were carried out by a Colombian firm, Avispa, using an Aerocommander.

Because of the small clearance of the Aerocommander during ground operations, the duct through which the FP was disseminated was made retractable. Figure 2-15 shows the generator in the aircraft. The small ground clearance is shown in Figure 2-16, where the downspout is in its fully extended position, about 12 in. clear of the fuselage at the leading edge.

Flight operations were conducted from the airfield at Turbo. Because of the lack of landmarks over the forest, the positioning of the release line was accomplished on the basis of airspeed and time considerations. The aircraft would approach the test area from downwind, fly a course along the line of the two 200 ft. towers (which were illuminated), and continue

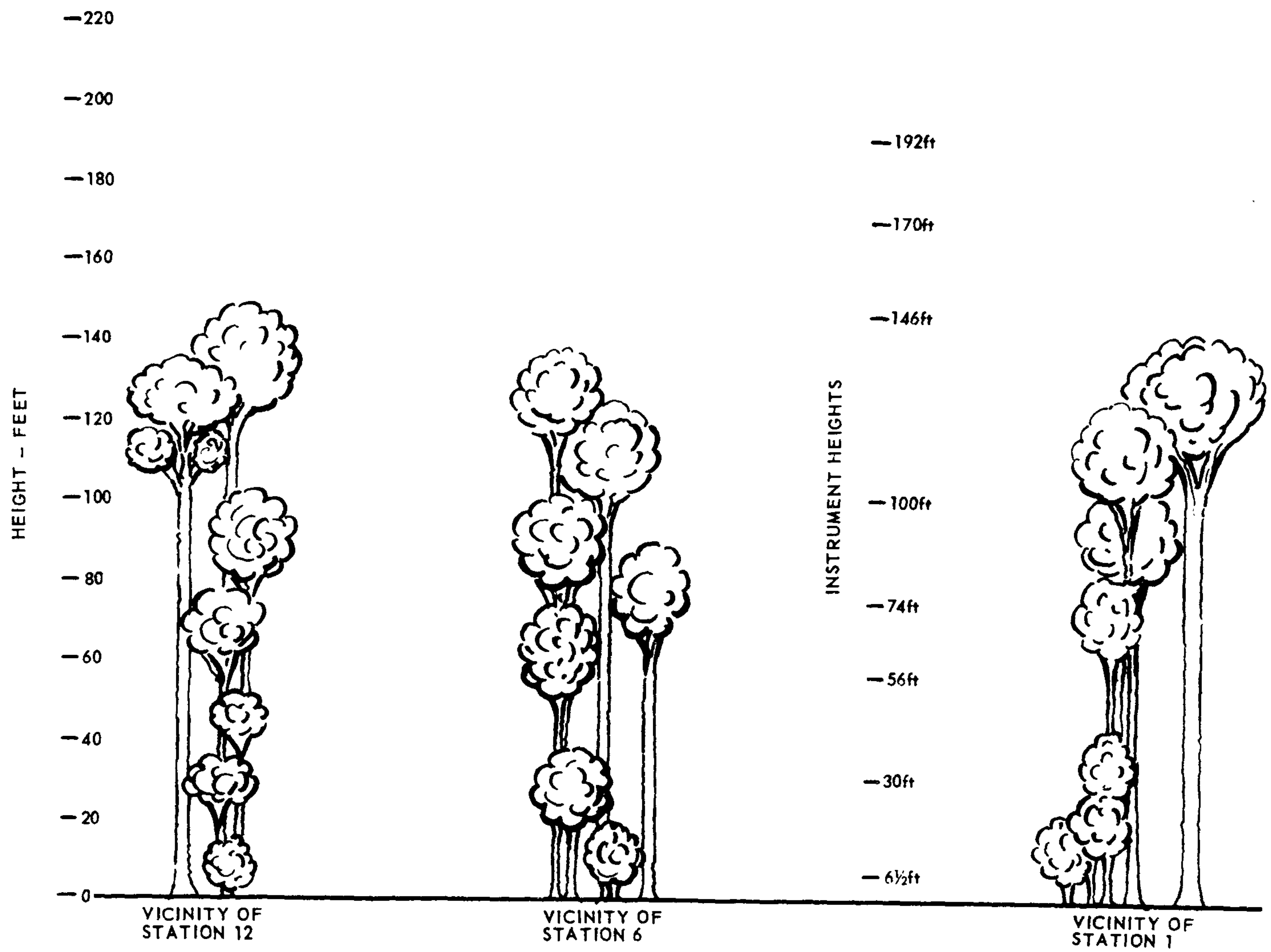


Figure 2-10 Sketch of Principal Structural Features of the Forest Showing Heights of the Eight Sampling Levels

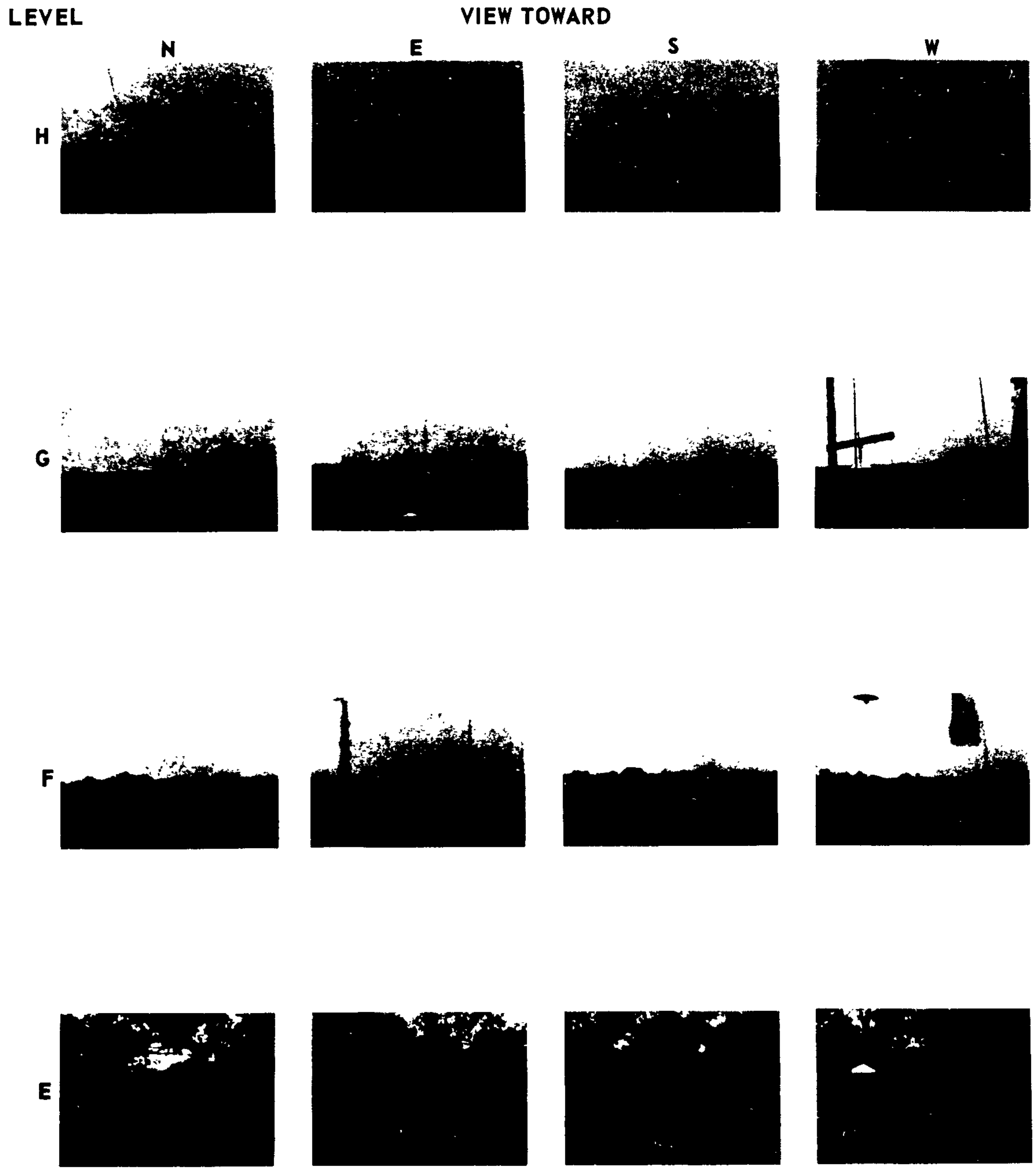
upwind from the last tower for the time required to traverse the distance called for in the plan for that particular test. At that time a righthand turn was made and, still on a time and airspeed basis, the airplane would fly six miles and make a 180 degree turn in order to return on a course normal to the line of the instrument array at the prescribed distance from the upwind tower. The FP release was made over a ten-mile line centered on the axis of the array. At no time during the operations was it necessary to deviate from a true 270 degree course during the release nor to adjust the center of the release line because the wind direction did not parallel the array. A sketch of the flight plan is shown in Figure 2-17.

Because of the lack of night flying facilities at the Turbo airfield, night operations required that the takeoff be prior to sundown and that the aircraft loiter until the release time, which was normally scheduled at 1900 hours, approximately one hour after sunset. At the conclusion of the FP drop, the airplane flew to a private airfield which had night lighting facilities, approximately 40 minutes flying time east of the test area. The plane returned to Turbo the following morning.

2.6 FIELD PROCEDURES

All day trials began at 0700 EST except for trial 3, which began 30 minutes later. All night trials began at 1700. The release of FP began two hours after the start of each trial. Each trial consisted of twenty half-hourly sampling intervals. To be ready to begin at 0700, it was necessary for the field crew to leave the camp at first light. Figure 2-18 shows the crew setting out on the trial prior to trial 3.

The assignment of manpower was as follows. Two Americans and one Colombian were stationed at each of the 200-ft towers, where they were responsible for the operation of the generators, the meteorological sensors and recorders, the timers (which cycled rotorod samplers every 30 minutes) and the changing of rotorods at eight levels. Figure 2-19 shows the changing and labelling of rotorods at the north tower. The remaining twelve stations were manned by Colombians, who worked in pairs, each being responsible for the changing of rotorods at three stations. All rods had been coated in advance with silicone grease, and labels to identify the time and place of each sample had been stored in the rotorod boxes for sequential use.



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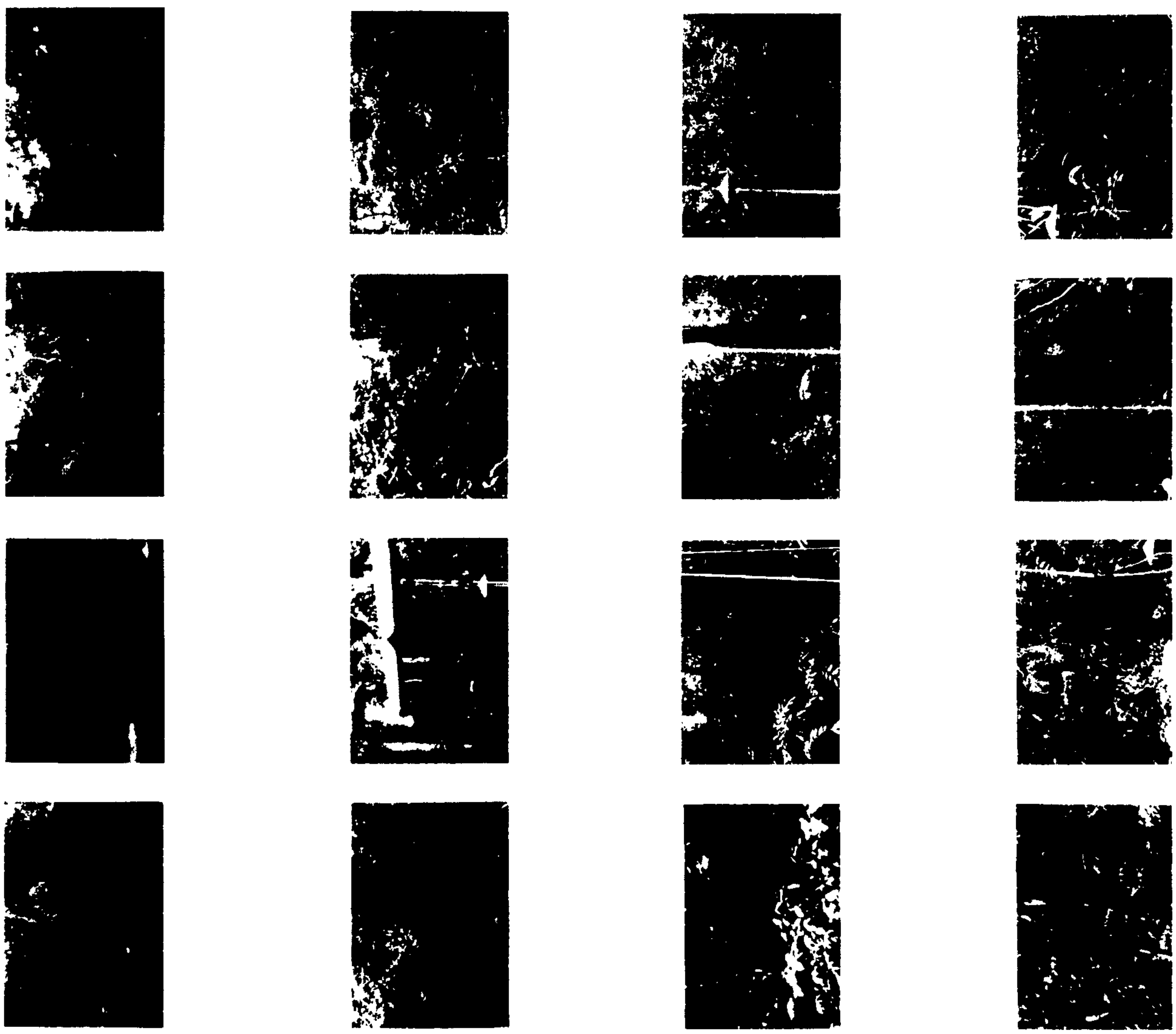

Figure 2-11 The Forest as Viewed in Four Directions From the Eight Levels on the North Tower

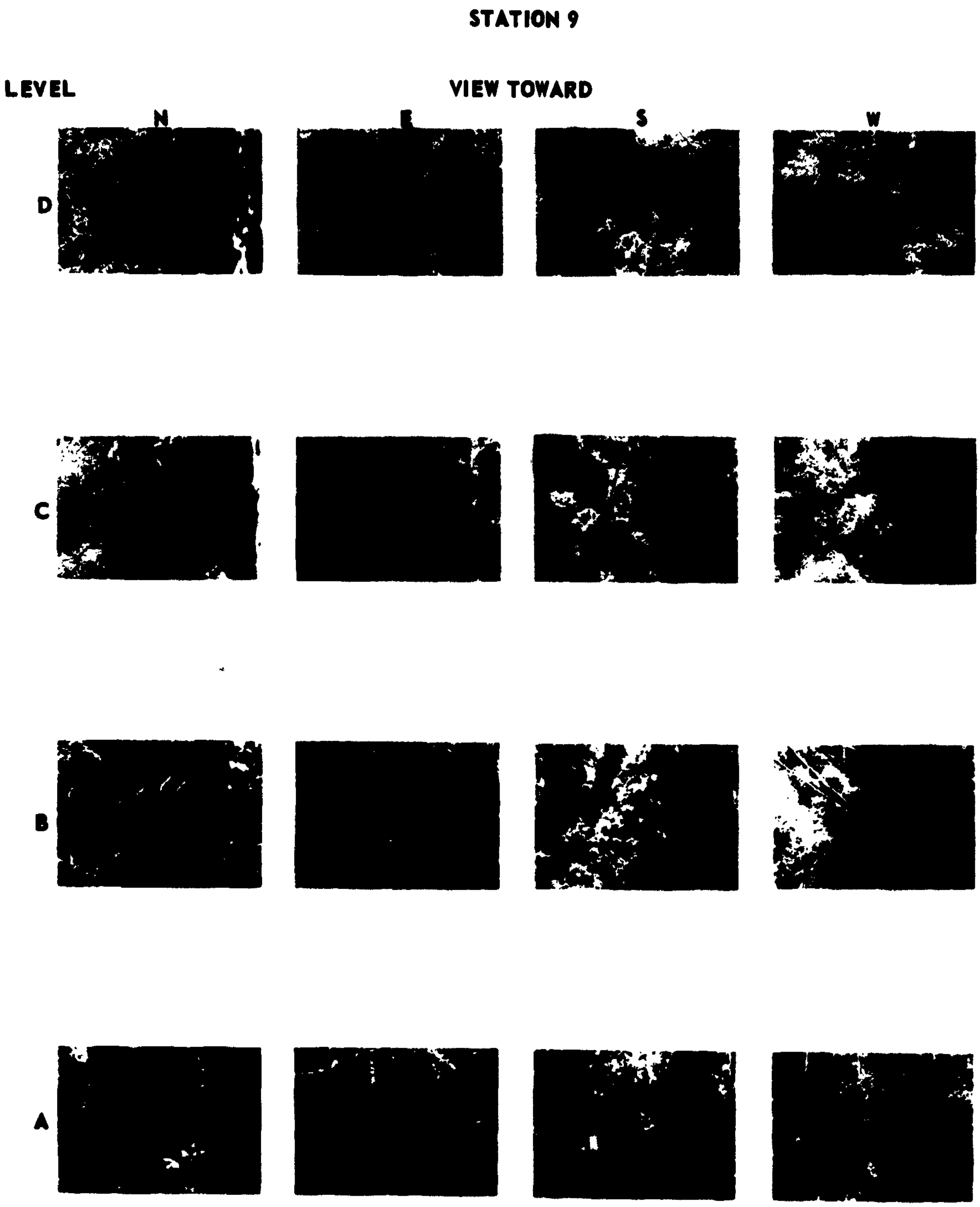

Figure 2-12 The Forest as Viewed in Four Directions From the Four Levels at Tree Station 9

Figure 2-13 Typical Lower Growth in the Study Area Between Stations 6 and 14

Figure 2-14 A Typical Plank Buttressed Tree and Vines and Ferns Which Characterize the Tropical Rain Forest

Figure 2-15 Interior View of the Aerocommander with FP Disseminator Installed

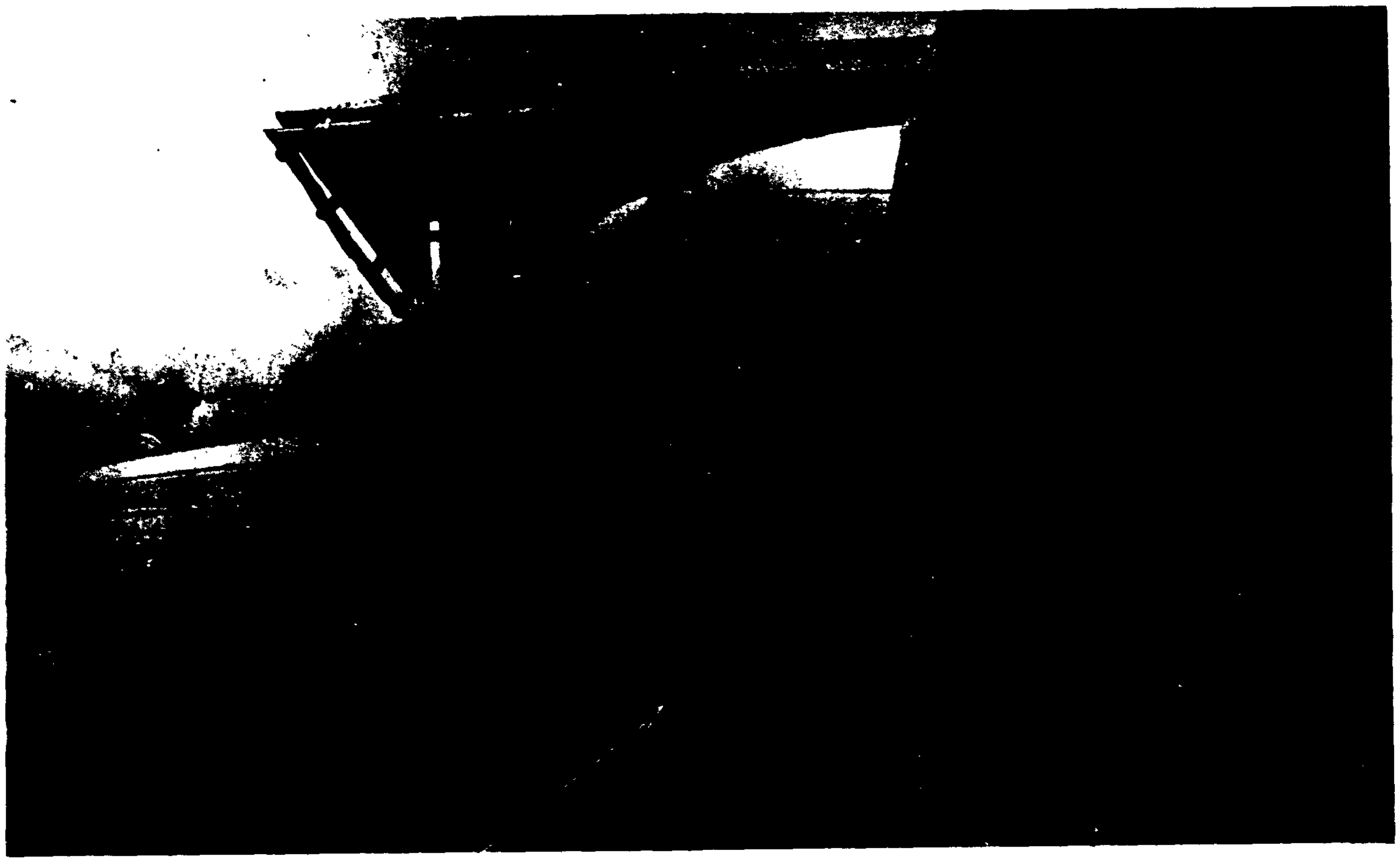

Figure 2-16 View of the Aerocommander Showing Projection of Disseminator Downspout When in Operating Position

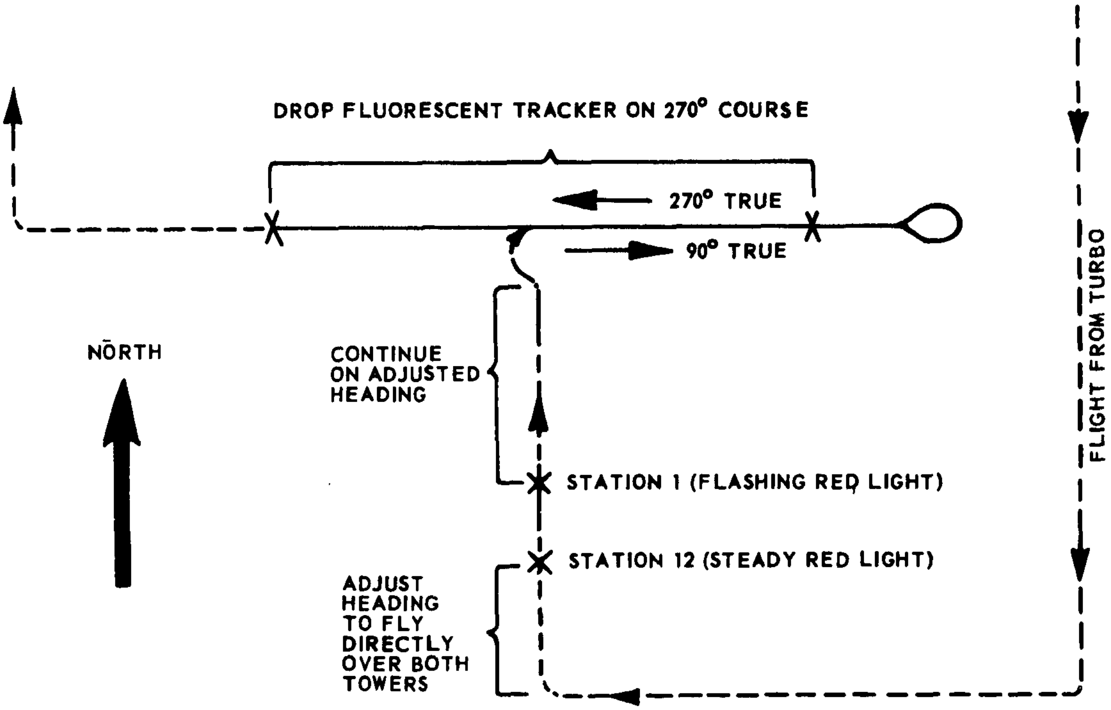

Figure 2-17 Typical Flight Plan During an FP Release in Relation to the Sampling Array

Figure 2-18 Field Crew Setting out on Trail to Test Array Prior to Trial 3

Figure 2-19 Changing Rotorods and Attaching Labels at North Tower During Trial 1

Two sets of rotorod samplers were installed at each station, one to the west of the supporting tower or tree, and the other to the east. While one set of samplers was in service, rods were charged on the other set. Timing switches were used to reverse the sense of rotation every 30 minutes and to alternate from set to set every hour. Thus, every rod collected one sample during clockwise rotation and another during counterclockwise rotation.

A set of special forms had been developed for the keeping of complete records. Routine duties during all trials included the preparation of logs on these forms, the entry of frequent time checks on the wind and temperature strip charts, the changing of magnetic tapes, and regular observations of the temperature of the water bath which contained the reference junction of the tower temperature facility. These observations provided the bench mark needed to obtain absolute rather than relative temperatures. Occasional power failures were dealt with quickly by cutting in one of the spare generators. Essential repairs to equipment were carried out between trials.

At the conclusion of every trial, a check of successfully exposed rotorods was made back at the camp. All rods, strip charts, magnetic tapes, and completed forms were then packaged and shipped out for analysis.

SECTION 3

THE OBSERVED DISTRIBUTION OF FP

This is the critical section of the report, since as pointed out in the introduction, the FP data must disclose the nature of the ventilation processes in the tropical rainforest. The data collected in 13 trials are presented here at some length with special emphasis on common features which may reveal mechanisms. The techniques employed in summarizing the data in this section are devices to focus attention on one aspect at a time. They are to be understood as convenient analytical procedures rather than diffusion models. The interpretation of the experimental results comes later in Section 4 where the penetration processes are described in qualitative terms, and in Section 5 where they are given quantitative expression in a mathematical diffusion model. Table 3-1 summarizes release data and general weather for the trials, and indicates whether the trial was during the day or night.

TABLE 3-1

SUMMARY OF FIELD TRIALS

Trial Number	General Weather	Distance to Release Line (Miles)	Ht. of Release above ground	Date of Trial Beginning
1	Sunny day	3	250	March 9, 1962
2	Cloudy day	2	200	March 12, 1962
3	Sunny day	3	200	March 15, 1962
4	Clear night	3	250	March 20, 1962
5	Cloudy night	5 (South)	300	March 24, 1962
6	Clear night	4	300	March 26, 1962
7	Cloudy night	4	300	March 28, 1962
8	Cloudy night	4	300	March 29, 1962
9	Cloudy night	1	300	March 31, 1962
10	Cloudy night	1	300	April 9, 1962
11	Cloudy night	1	300	April 10, 1962
12	Cloudy day	1	300	April 12, 1962
13	Cloudy night	3	300	April 13, 1962

3.1 CONCENTRATION AND DOSAGE DEFINED

A rigorous definition of the concentration of any airborne material specifies the amount of material present in a unit volume of air. A single aerosol of uniform size may be expressed as number of particles per unit volume of air. Hence, the concentration of FP is appropriately expressed in terms of the number of particles per cubic meter.

The formal relationship between concentration, χ, and dosage, D, during the time interval t_1 to t_2 is expressed by

$$D = \int_{t_1}^{t_2} \chi \, dt$$

Only a few kinds of air samplers yield instantaneous concentrations which can be used in this way to compute dosage. Most samplers measure the average concentration $\bar{\chi}$ during some specified time interval Δt, and the expression for dosage becomes

$$D = \sum_{i=1}^{\infty} \bar{\chi}_i \, \Delta t$$

where $\bar{\chi}_i$ is the average concentration during the ith sampling interval.

Rotorod samplers yield an average concentration -- in this experiment, a half-hourly average. The samplers are designed to rotate at the same speed, and since the rods are of identical dimensions, each sampler sweeps out the same volume in a half hour. Collection efficiency of the rods, as coated, is less than 50 per cent but can be assumed constant for all rods. Consequently the expression

$$\bar{\chi} = k n$$

may be used for the half-hourly average concentration of FP where n is the number of particles on the exposed rod and k is a constant embracing speed of rotation, geometry of the rods, efficiency of the sampler, and length of the sampling interval.

The assay of rotorods results in the determination of n, the number of FP particles on each rod. It is possible from this number to compute the corresponding value of the mean concentration. But since every relationship in time and space between mean concentrations is determined by the relationship between counts, it was decided to work directly with the counts. Therefore, throughout the analysis, half-hourly counts are treated as if they were in fact concentrations, and the sum of all the counts at any station is considered to be the dosage for that trial. Needless to say, there is no loss of generality in this procedure.

3.2 CONCENTRATION VERSUS HEIGHT

The following procedure was used to determine concentration versus height profiles which would be representative of the entire test array. Beginning with the fifth half hour *, the mean concentration was determined for each level from all available samples. There were 14 stations at the four lowest levels, but only the three towers at upper levels as shown in Figure 2-7. At the top three levels, no value was included if only one station reported. The same procedure was repeated for the succeeding half hours until the FP concentration returned to background levels.

The computed mean counts or concentrations are presented in Table 3-2 for sampling intervals 5, 6, and 7 only and portrayed graphically in Figures 3-1 to 3-3. A rapid scan of Table 3-2 suffices to show that the highest count in each trial is at one of the three above-canopy levels, but that these maxima range from 488 at 192 ft in trial 8 to 8936 at 170 ft in trial 10. For this reason, the scale for FP counts has been varied from trial to trial in Figure 3-1, 3-2, and 3-3 so that the same space on the page may be allotted to each trial. This amounts to an informal type of normalization which promotes easier comparison between separate trials.

Some generalizations can be made from these figures. Interval 5, which follows the release of FP, is characterized by a strong downward gradient of FP, and usually records the highest count of the entire trial.** The vertical profile alters rapidly thereafter and within 30 to 60 minutes the gradient becomes directed upward. The change is noticeably slower however in trials 5, 9, and 11. This upward gradient remains in effect until the FP counts have fallen to background levels.

*FP was released at the beginning of the fifth half hour.

**The only exception, trial 5, was a case in which the release of FP was made 5 miles from the array with 5 mi/hr winds. As a result, maximum above-canopy counts were delayed until interval 6.

TABLE 4-2

MEAN FP CONCENTRATIONS AT EIGHT LEVELS DURING INTERVALS 5, 6, AND 7 FOR 13 TRAILS (LEVELS GIVEN IN FEET ABOVE GROUND)

Trial	Interval	Levels 6.5	30	56	74	100	146	170	192
1	5	727	875	1002	1027	1256	msg	msg	msg
	6	255	161	154	94	72	5	msg	msg
	7	10	8	6	3	10	10	msg	msg
2	5	64	604	1640	1995	1954	2880	2991	2858
	6	760	929	863	706	724	468	422	356
	7	121	70	47	41	38	51	msg	msg
3	5	142	413	636	745	756	937	1058	980
	6	528	494	397	359	305	260	251	206
	7	132	80	45	35	44	37	55	59
4	5	67	443	739	913	1321	1642	1778	1778
	6	524	627	667	542	478	372	382	327
	7	364	298	174	119	90	77	80	63
5	5	9	12	18	24	79	msg	1508	2328
	6	94	161	244	311	546	msg	5048	5737
	7	533	521	521	579	968	731	470	366
6	5	99	474	828	1005	1226	1421	1412	1341
	6	264	273	195	130	133	85	86	88
	7	116	74	34	16	10	18	30	22
7	5	166	395	574	641	663	797	825	812
	6	299	290	222	175	168	133	118	120
	7	76	46	33	23	14	19	36	msg
8	5	28	113	224	285	320	420	428	488
	6	255	344	357	365	350	357	306	288
	7	91	68	36	34	16	26	24	20
9	5	386	677	1085	2141	3157	4489	6054	6258
	6	3101	2665	2420	2455	1926	1111	1072	960
	7	1510	1626	1467	1377	1549	789	260	176
10	5	538	1987	4382	5617	7460	8222	8936	8755
	6	1931	1661	1377	1267	808	330	383	440
	7	591	507	343	240	215	51	msg	38
11	5	174	337	597	731	1599	3794	5097	5336
	6	1860	2048	2209	2231	1872	2824	3054	2708
	7	1472	1625	1593	1277	957	375	362	321
12	5	260	525	2146	3586	6939	7233	7808	7786
	6	1704	4185	6676	6371	6648	5670	6121	4980
	7	3328	2294	1501	922	867	333	342	307
13	5	252	1378	2232	3564	4412	4672	5006	4972
	6	1414	1485	1361	1248	862	442	356	349
	7	603	484	204	127	91	94	152	228

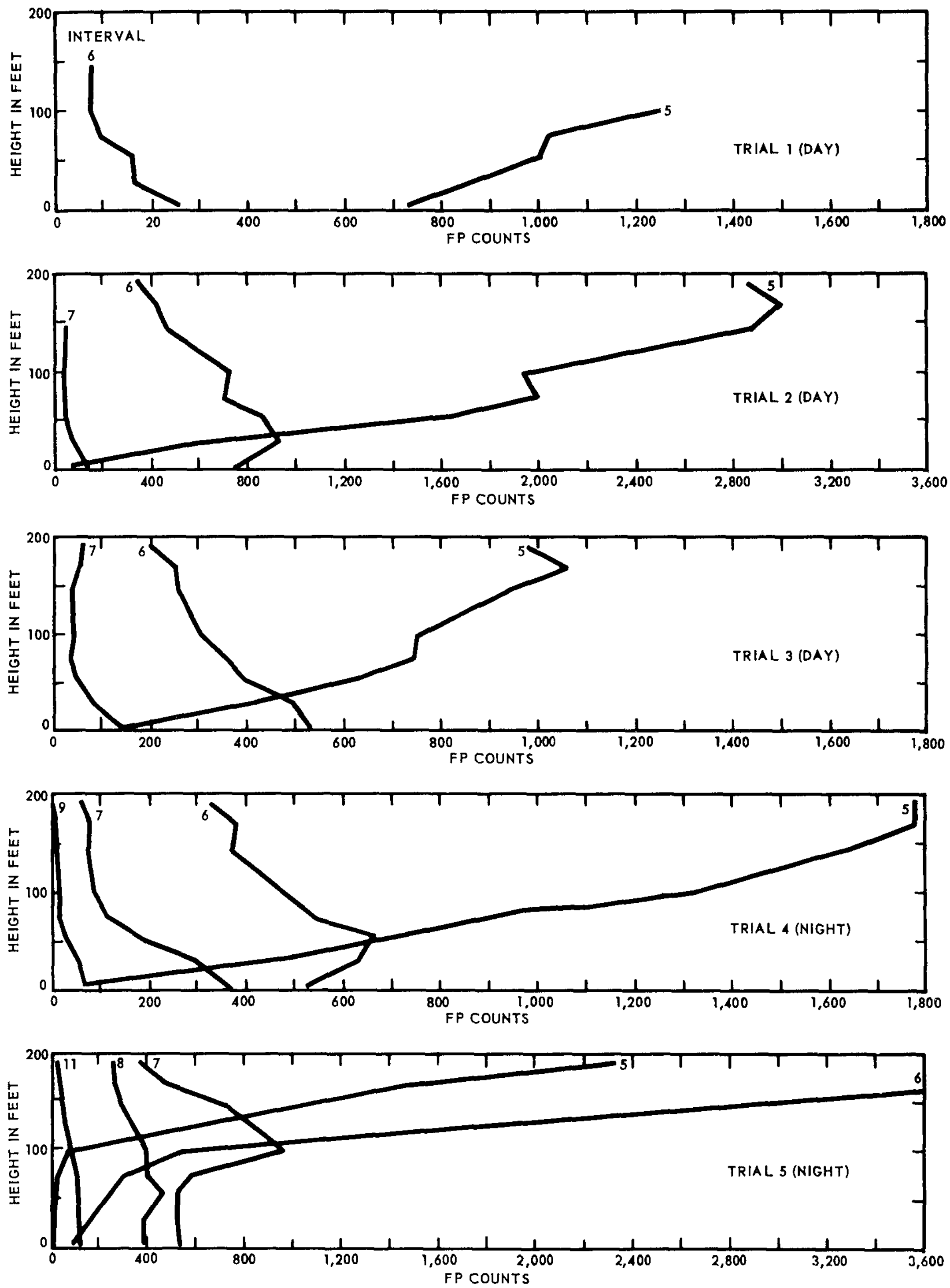

Figure 3-1 Mean FP Concentration Versus Height During Separate Half Hourly Intervals, Trials 1-5. (Note Different Abscissa Scales)

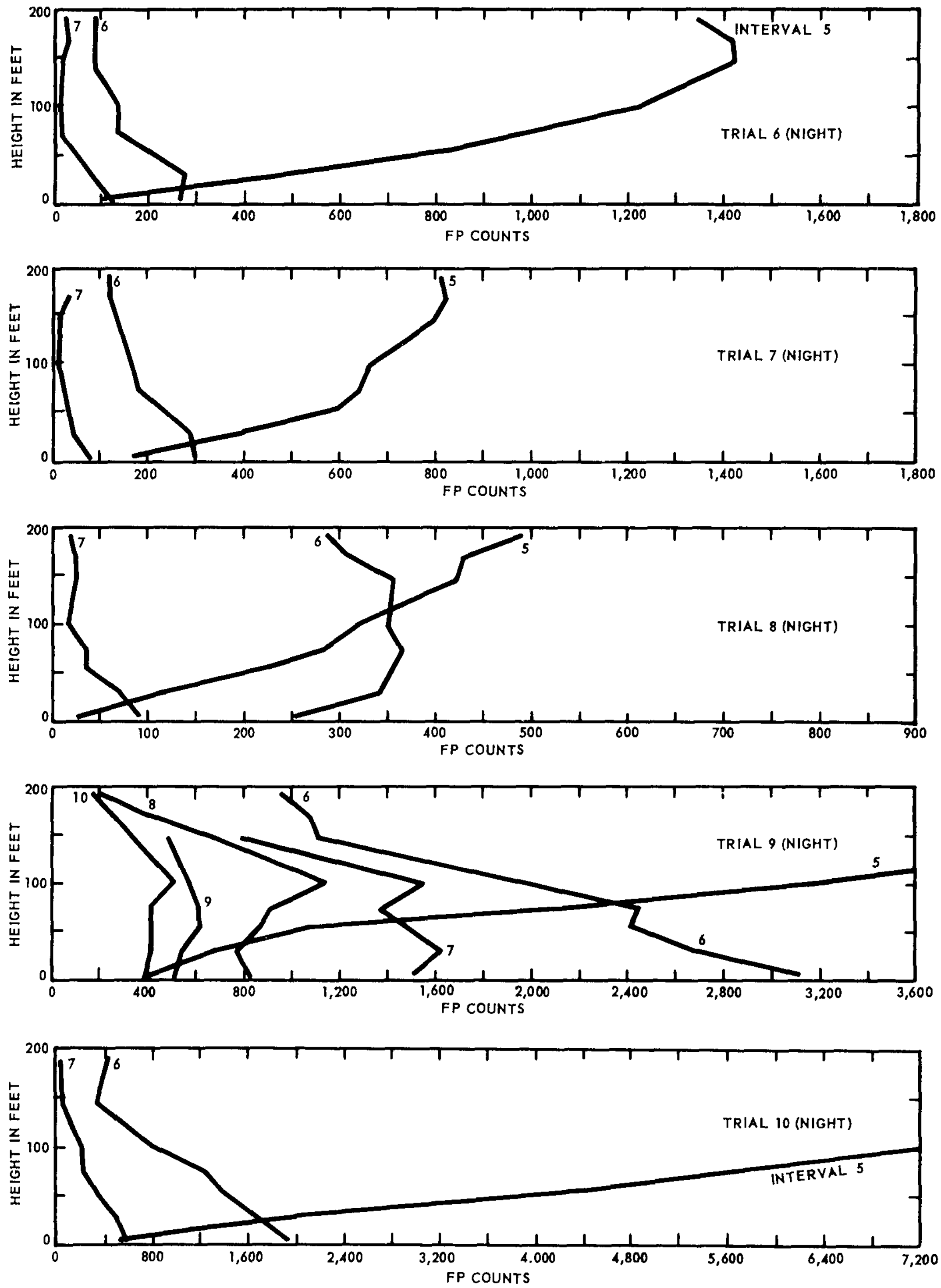

Figure 3-2 Mean FP Concentration Versus Height During Separate Half Hourly Intervals, By Trials (Note Different Abscissa Scales)

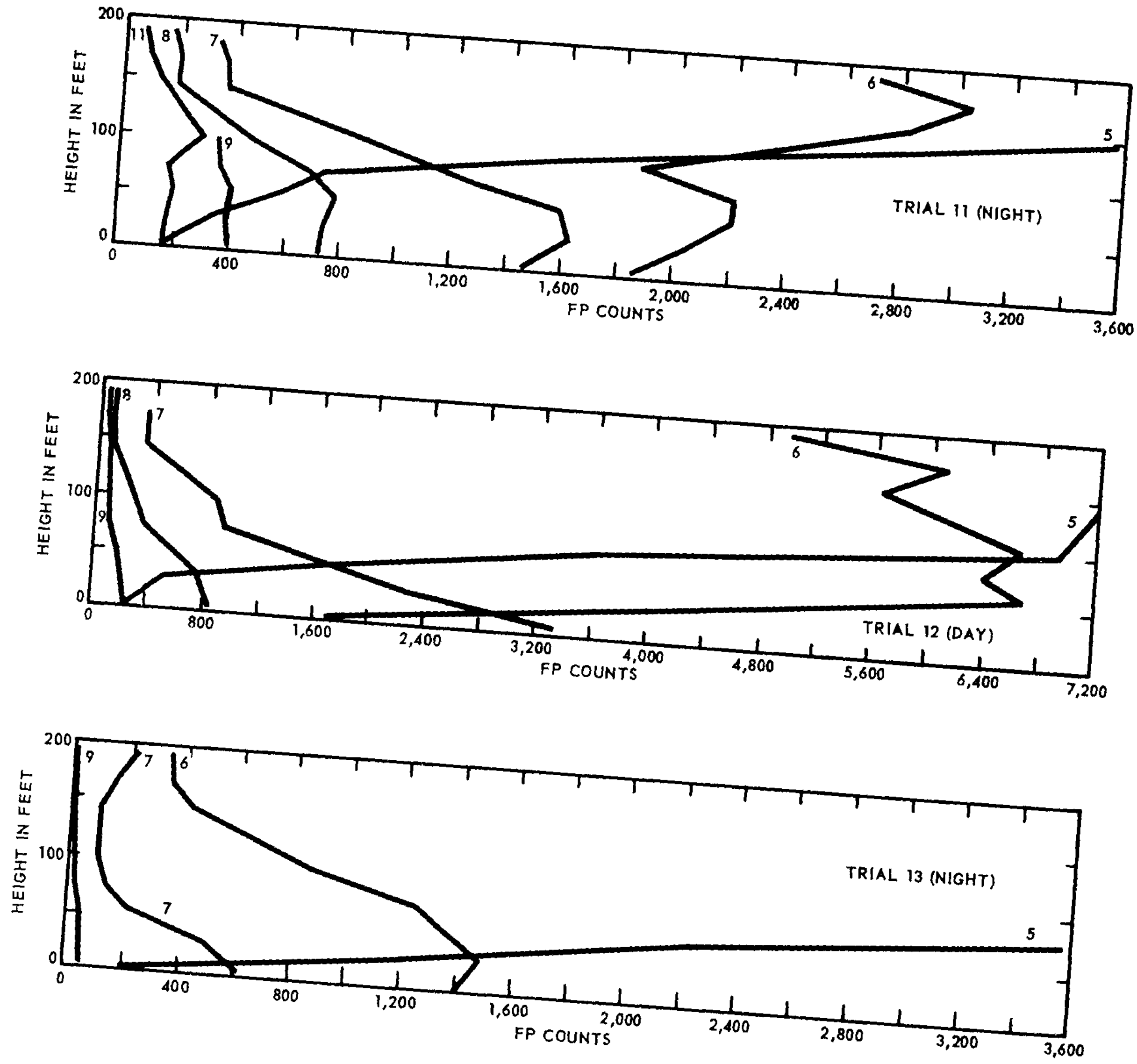

Figure 3-3 Mean FP Concentration Versus Height During Separate Half Hourly Intervals, By Trials (Note Different Abscissa Scales)

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The cycle from downward gradient, to upward gradient, to disappearance, may be rapid, as in trial 1 where background is reached in interval 7, or slow enough to reveal the transitional profile as in trials 2, 4, 5, 8, 11 and 12. In all trials, however, it is clear that the fumigation exhibits an initial brief phase in which the gradient of FP is downwards, and a longer second phase of variable duration in which the gradient of FP is upwards.

3.3 CONCENTRATION VERSUS TIME AT 6.5 FT

To consider this aspect of FP distribution, histograms of concentration versus time have been developed for each of the trials. To facilitate comparison between trials, a simple normalizing technique was used that is analogous to the distribution graphs used in hydrology to investigate storm run-off. First, for each trial the average FP count for all 14 stations is computed for each interval from 5 through 20. This covers an 8 hour period beginning at the time of drop. Mean 6.5 ft dosage is obtained by summing the counts for each interval. It is then possible to compute the percentage of the total dosage that occurred in each interval from the expression

$$\text{i-th interval percentage} = \frac{100\,\chi_i}{\sum_{i=5}^{20} \chi_i}$$

where χ_i is the mean count for all 14 stations in the i-th sampling interval.

The normalized data appear as histograms in Figures 3-4 and 3-5. A common feature of all 13 trials is the positively skewed rather than Gaussian nature of the histograms. But the 13 graphs differ in such features as the magnitude of the peak half hour and the duration of the entire fumigation. There are striking differences, for example, between trial 1 with its high peak and 1.5 hour duration and trial 5 with its low peak and 4.5 hour duration. Even greater persistence was observed in trials 9 and 11 where the fumigations continued nearly 8 hours. It is evident that there are factors at work which are variable, and are presumably meteorological. The identification of these meteorological factors is discussed in Section 5. It is enough to assert at this point that the differences between the 13 graphs of Figure 3-4 and 3-5 can be accounted for by meteorological factors.

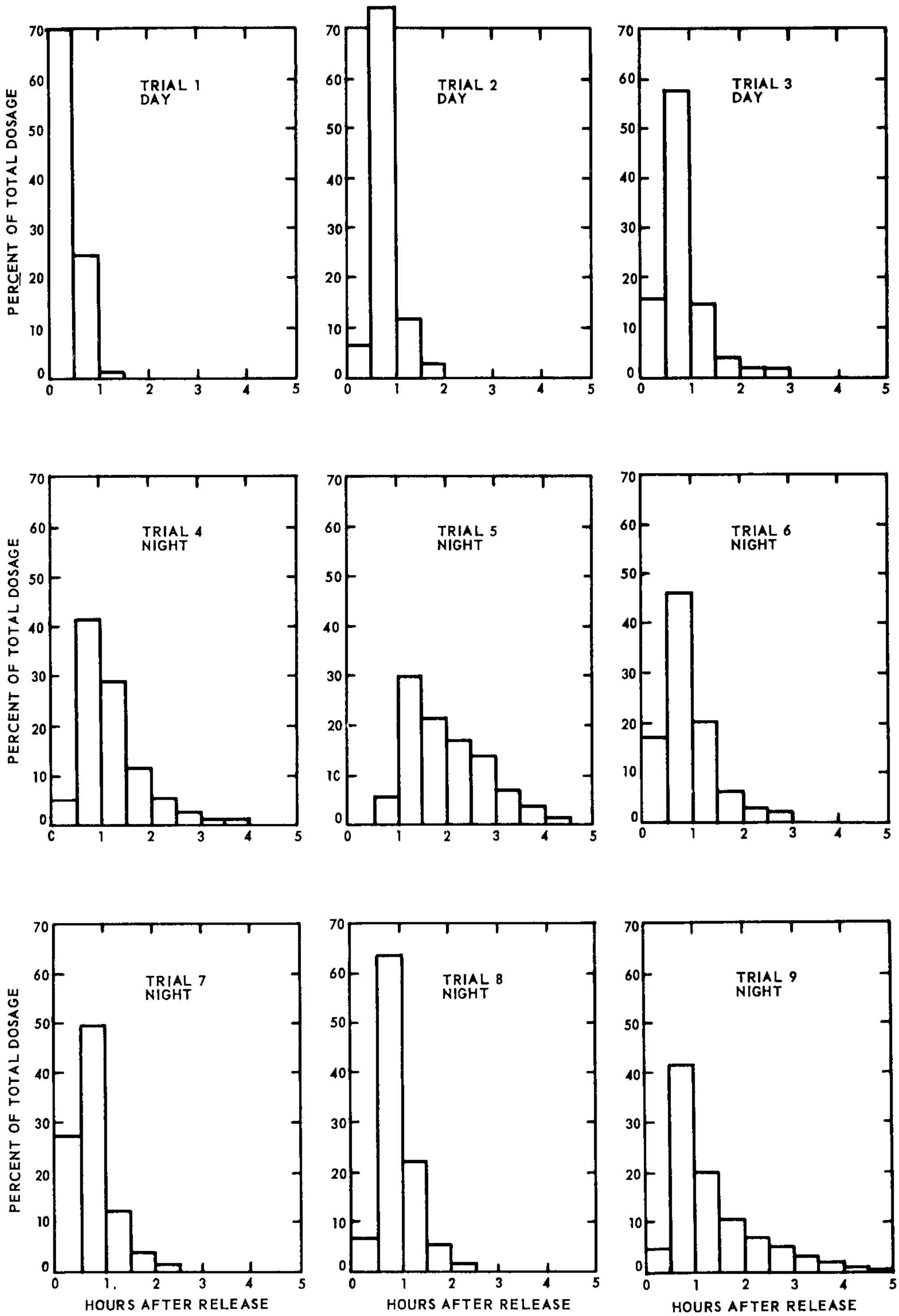

Figure 3-4 Mean 6.5 ft Concentration Versus Time, Trials 1-9

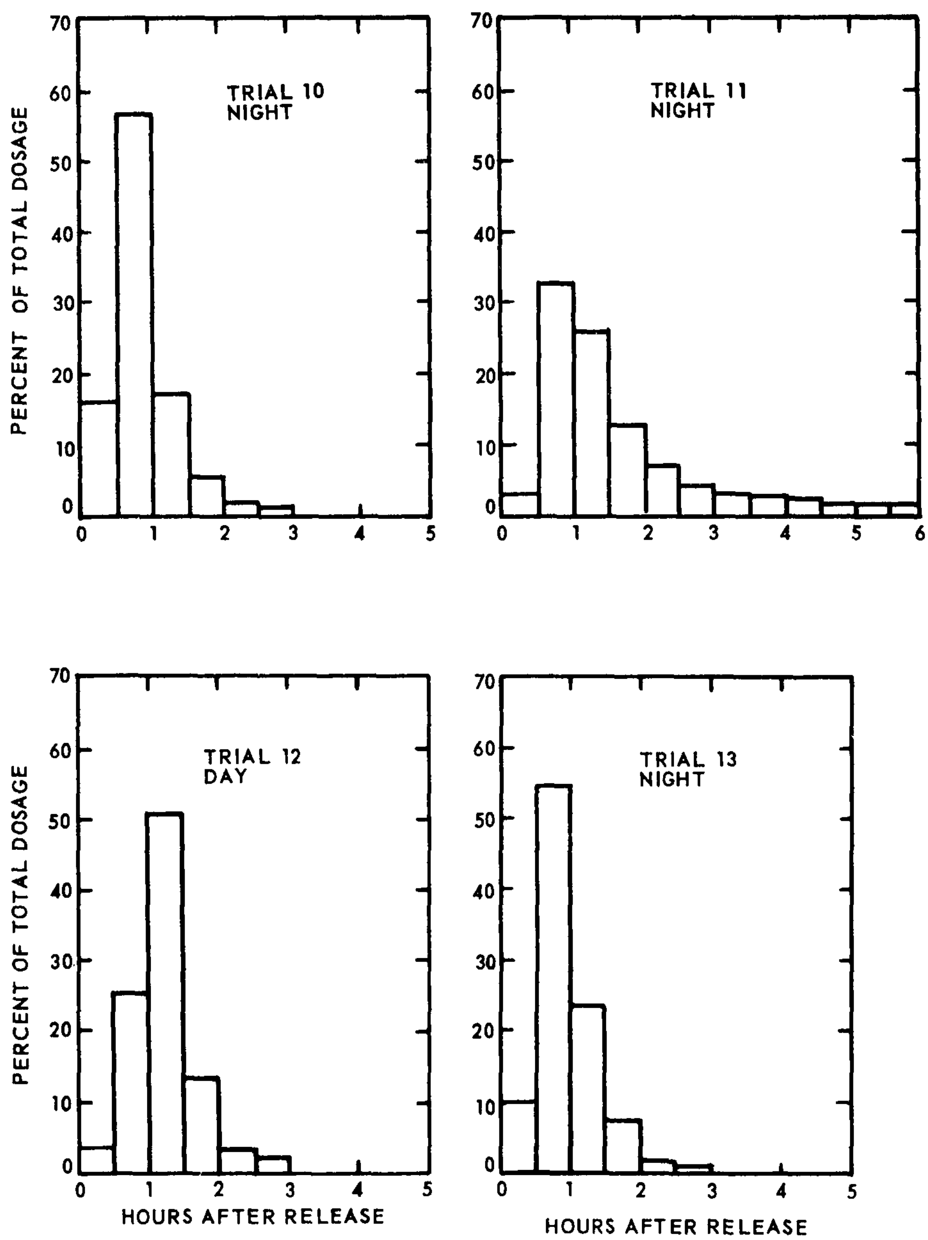

Figure 3-5 Mean 6.5 ft Concentration Versus Time, Trials 10-13

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3.4 ADVECTIVE PROCESSES

The first appearance of FP within the test array is largely due to advective effects. Data are presented below to confirm that this is so for the present experiment. It is neither evident nor easy to establish, however, whether advection plays an important role in the disappearance of FP below the canopy. A method of isolating the effect of advection below canopy is outlined in this section and it is shown that its role is minor in determining the dosage.

In Section 3.3 a technique was described for normalizing mean half-hourly concentrations and plotting concentration, expressed as a percent of total dosage, versus time. The same technique may be applied to the h-level, and the a- and h-levels (6.5 ft and 192 ft) may be compared. Table 3-3 contains normalized counts for levels a and h for intervals 5, 6, and 7. It should be noted that this method of normalizing does not permit inter-level comparisons of concentration since the concentrations are expressed as a percentage of dosage at that level. Section 3.2 contains comparisons of concentration versus height. The data of Table 3-3 are designed to compare the time histories of FP above and below the canopy. They show that the largest fraction of the h-level dosage occurs in interval 5, the first interval after release. This occurs because the FP plume is carried along by the wind and reaches level h without interference from the canopy. The presence of a small amount of FP at level h during intervals 6 and 7 may be attributed to emanations from the forest. The occurrence of peak concentration at the a-level is usually delayed one interval since the FP must penetrate the canopy after arriving overhead. Figure 3-6 illustrates the same features graphically as they are revealed in trials 4, 6, 9, and 12.

In isolating the role of advection at 6.5 ft it seemed best to study the time history of FP concentration at the 12 stations which were spaced at 100 meter intervals along the north-south line. Twelve of the thirteen tests were carried out with northerly winds. Consequently, if advection were important, one might hope to observe the orderly disappearance of the FP, first at station 1, then station 2, and so on through to station 12. The difficulties with this ideal approach are that the return to background FP counts (usually zero) is asymptotic and hence poorly defined so that, at best, timing of an event is possible only to the nearest half hour. Once again it seemed appropriate to adopt some normalizing procedure that would permit combining all the trials except 5, for which the wind was southerly.

TABLE 3-3

FP CONCENTRATION VERSUS TIME AT LEVELS a AND h (6.5 AND 192 FT)

Trial	Interval	a-Level Concentration in Percent of a - level Dosage	Level Concentration in Percent of h-Level Dosage
1	5 6 7	70.8 24.8 1.0	msg msg msg
2	5 6 7	6.3 74.6 11.9	88.9 11.1 0.0
3	5 6 7	15.4 57.4 14.4	76.7 16.1 4.6
4	5 6 7	5.3 41.5 28.8	79.9 14.7 2.8
5	5 6 7	0.5 5.2 29.7	25.8 63.5 4.0
6	5 6 7	17.3 46.2 20.3	91.2 6.0 1.5
7	5 6 7	27.4 49.4 12.5	87.1 12.9 0.0
8	5 6 7	6.3 63.7 22.2	59.8 35.3 2.5
9	5 6 7	5.2 42.0 20.4	78.2 12.0 2.2
10	5 6 7	15.8 56.8 17.4	94.4 4.7 0.4
11	5 6 7	3.1 32.9 26.0	60.8 30.9 3.6
12	5 6 7	4.0 25.9 50.6	58.9 37.6 2.3
13	5 6 7	9.8 54.8 23.4	86.8 6.1 4.0

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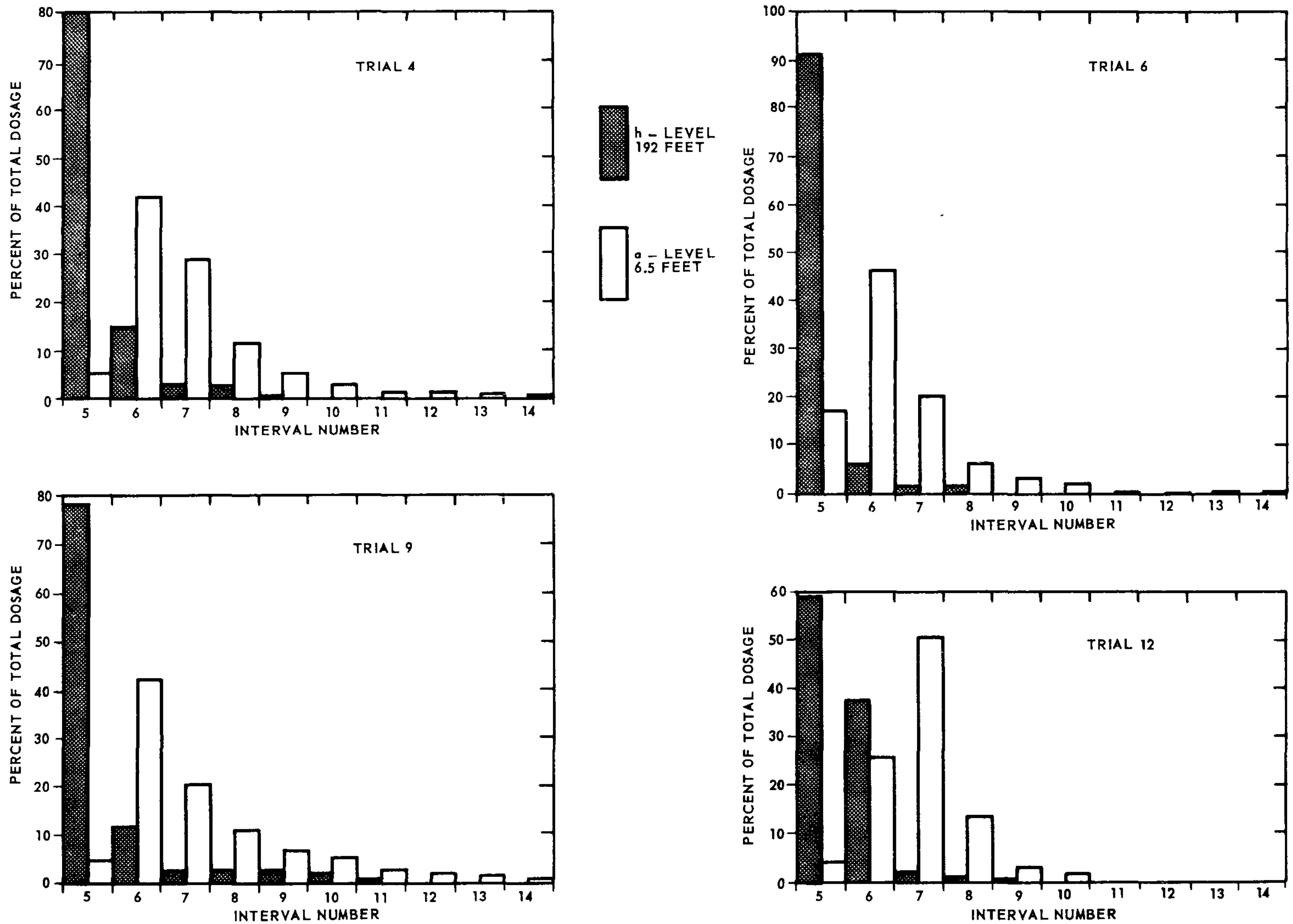

Figure 3-6 FP Concentration Versus Time Above, (h-Level), and Below, (a-Level), the Canopy for Four Representative Trials. Each Interval Equals 30 Minutes

The data processing procedure for a single station will be described, and it may then be understood that stations 1 through 12 were treated in the same way. The procedure consisted of expressing all half-hourly FP counts as a percentage of the total dosage during that trial, and then combining the twelve trials so that a mean percentage could be computed for each of the intervals 5 through 20. Beginning with station 1 and trial 1, the 6.5-ft dosage was first computed and then the mean concentration for each interval was expressed as a percentage of the dosage. The procedure was repeated for trials 2 through 13, with trial 3 omitted for this station only because of contaminated samples, and trial 5 omitted because of southerly winds. Then a mean percentage was computed for each half-hourly interval and finally, cumulative percentages were computed for each interval. Table 3-4 contains the results of this procedure when applied to station 1. The last column of Table 3-4 indicates that, on the average, 17.50 percent of total dosage occurred during the first half hour after release at station 1, 94.66 percent occurred during the first 2-1/2 hours and 99.02 percent during the first 5-1/2 hours.

The cumulative percentages for all 12 stations were then plotted on a graph of time versus distance from the north tower (station 1) as shown in Figure 3-7. For example, the number 17.50 which is the cumulative percentage at the end of one half hour at station 1 was plotted at the coordinate point, Time = 0.5 hrs. Distance from north tower = 0. It was planned to draw isopleths of percentage on Figure 3-7 for values of 50, 90, 95, 97.5, 99, and 99.5 percent. To assist in pinpointing the times for each of these percentages the ogive was constructed for each station, and times as read from the ogive were noted on Figure 3-7 by short line segments intersecting the distance coordinate for the particular station. The isopleths were then drawn as smoothly as possible.

In interpreting Figure 3-7 each isopleth should be examined separately from top to bottom of the page. It is clear that if the isopleths run perpendicular to the time axis, the FP fumigation at 6.5 ft is perfectly in phase at all 12 stations and there is no evidence of advection. If the lines slope down and to the right this indicates that the same event occurs progressively later as distance from the north tower increases and this suggests advection. However, it must be remembered that below-canopy winds averaged 0.4 mi/hr* and the time lags should be compatible with these speeds if simple advection is involved.

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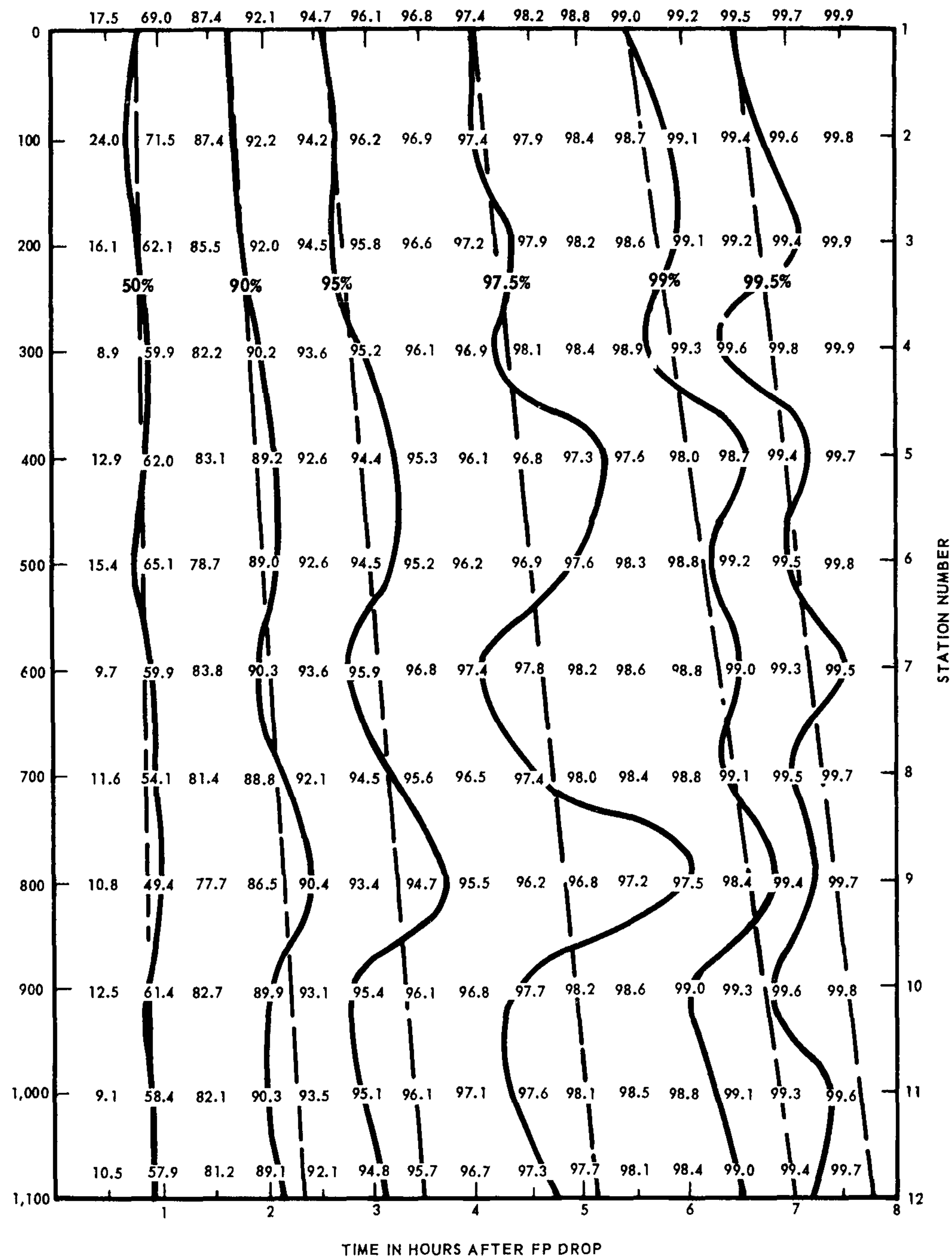
*Average wind speed as a function of height is discussed in Section 3.2, Part II, Volume II of this report.

TABLE 3-4

COMPUTATION OF MEAN CONCENTRATION VERSUS TIME BY TRIALS AT 6.5 FT, STATION 1
(ALL ENTRIES ARE IN PERCENTAGE OF TRIAL DOSAGE AT 6.5 FT)

Interval	1	2	4	6	7	8	9	10	11	12	13	Mean	Cum. %
5	64.6	3.9	3.9	10.5	35.9	5.5	8.7	40.6	3.7	2.3	8.3	17.50	17.50
6	32.1	88.4	53.0	63.7	44.1	68.0	47.4	45.9	41.6	17.0	65.2	51.49	68.99
7	1.0	4.0	25.0	20.2	12.8	13.8	14.7	8.2	16.9	64.8	21.3	18.43	87.42
8	1.0	0.5	6.0	1.5	4.1	0.8	7.6	3.2	13.0	11.2	2.7	4.69	92.11
9	0.1	0.5	3.6	1.3	1.1	0.6	7.9	11.3	8.0	2.7	0.9	2.55	94.66
10	0.0	2.3	1.7	1.0	0.1	0.2	6.1	0.5	3.0	0.8	0.4	1.46	96.12
11	0.3	0.1	1.8	0.3	0.4	0	2.4	0.1	1.4	0.5	0.4	0.70	96.82
12	0.3	0.1	2.4	0.4	0	0	1.6	0.2	1.4	0.3	0.2	0.63	97.45
13	0.1	0.1	0.8	0.1	0.1	1.8	1.3	0.1	3.8	0.2	0.2	0.78	98.23
14	0.1	0	1.1	0	0.4	0.8	0.8	0	2.6	0	0.1	0.54	98.77
15	0.0	0.1	0.1	0.4	0	0.4	0.3	0	1.3	0	0.1	0.25	99.02
16	0.0	0	0.1	0	0.1	msg	0.4	0	1.2	0	0.1	0.19	99.21
17	0.1	0	0.3	0	0.3	1.0	0.4	0	1.4	0	.0	0.32	99.53
18	0.1	0	0.2	0	0	0.6	0.3	0	0.6	0.1	0.1	0.18	99.71
19	0.1	0	0.1	0.1	0	1.0	0.1	0	0.2	0	0	0.15	99.86
20	0.0	0	.0	0.1	0.4	0.8	0.1	0	0.1	0	0	0.14	100.00



NOTE: PLOTTED NUMBERS ARE MEAN CUMULATIVE DOSAGE AT EACH STATION

Figure 3-7 Isopleths of Mean Cumulative Dosage in Percent
Plotted Numbers are Mean 6.5-ft Cumulative Dosages at
Each Station, Trial 5 Excluded

To assist in the interpretation of Figure 3-7, trend lines have been drawn through each isopleth. It may be noted that the variations about these lines increase with increasing distance downwind. Using the trend lines the 50 percent isopleth exhibits a total lag of 6 minutes from station 1 to station 12 which can be attributed to advection on winds of 7.5 mi/hr. Such a speed, however, is characteristic of above-canopy flow rather than below-canopy flow. The 90 percent isopleth shows an end to end lag of 40 minutes which may be attributed to advection on winds of 1 mi/hr which is still well in excess of below-canopy winds. The observed time lags for the isopleths of 95, 97.5, 99, and 99.5 percent are 54, 66, 93, and 75 minutes. The latter two may be accounted for by winds of 0.4 and 0.5 mi/hr which is only a little above the indicated speeds below canopy.

It is concluded, therefore, that the disappearance from under the canopy of at least 90 percent of the FP is achieved primarily by upward transport whereas the very small residue that remains behind at 6.5 ft i.e., the last 1 or 2 percent, disappears from the array as a result of simple advection at that level.

The same conclusion may be developed in an entirely independent manner as follows. The upwind edge of the FP cloud is approximately fixed by the touchdown point of the source cloud on the tree tops. The time for the upwind edge to reach the array is then readily estimated from the average below-canopy wind. If this time is substantially greater than the observed time for the FP to disappear at 6.5 ft., it is clear that advection does not account for its disappearance.

Touchdown points were computed using a general expression for dosage computations given by Milly(1). The below-canopy wind between the surface and 100 feet averaged 4 percent of the 200 ft wind speed. This value was used with the average 200 ft wind during the period of observed dosage to obtain an average below-canopy wind. The computed advection times are compared in Table 3-5 to the observed times for 95 percent of the dosage to occur. Only in trials 10 and 11 does it appear that disappearance of FP was caused by advection. In all other trials it is conclusively shown that advection cannot have accounted for the disappearance of the FP.

3.5 DOSAGE VERSUS DISTANCE ACROSS WIND

Two steps had been taken to eliminate cross-wind variations of dosage. First, the length of the cross-wind line source was set at 10 miles. Secondly,

Table 3-5

Computed Time for Advective Disappearance of FP Compared to Observed Time of Disappearance

Trial	Distance Station 1 to Touchdown	Average Below-Canopy Wind Speed	Computed Time After Drop for Upwind Edge to Advect to Station 1	Observed Time* After Drop for 95% of Dosage at Station 1
1	4700 m	15.0 m/min	314 min	60 min
2	3100	13.9	223	90
3**	4600	10.7	430	120
4	4200	10.7	392	210
5***	6900	6.4	1080	420
6	6200	12.9	480	120
7	6100	11.8	520	120
8	6300	13.9	450	270
9	1400	4.3	330	240
10	1200	9.7	120	150
11	1500	5.4	280	300
12	1400	3.2	440	120
13	4400	9.7	450	120

* Times taken from Table 3-4

** Times and Distances Refer to Station 2

*** Times and Distances Refer to Station 12

the test site had been selected because of its freedom from the influence of holes and drainage winds. Nevertheless, two sampling stations, numbers 13 and 14, had been installed 200 m east and west of station 6 to confirm the absence of cross-wind effects.

In examining the observed dosages at Stations 13, 6, and 14 for evidence of cross-wind effects, we look for effects which appear in the average of all trials, that is, effects due to environmental factors such as holes in the canopy or drainage winds. However, before combining the 13 trials it is necessary to normalize the data in some way so that variations in the absolute dosage from trial to trial will not bias the result. To accomplish this, the observed dosage at each level of each station was expressed as a percentage of the above-canopy dosage. Details of this procedure are given in Section 3.7. The resulting normalized dosages are given in Table 3-6.

There are a number of alternative ways of treating the data of Table 3-6 for evidence of cross-wind effects. In all of them we may combine the four levels, each of which is below canopy, because the effects of interest will affect all levels. One way is to compute the linear regression of dosage on cross-wind distance and test the computed slope of the line to see if it differs significantly from zero. A second way is to perform a rigorous analysis of variance of the data for evidence of between-station differences. A third way is to compute the mean below-canopy dosage for each station and test the means, two at a time, for significant differences using the t-test. When only three stations are involved the third method is not particularly tedious and was used.

The following results were obtained. Mean dosages at stations 13, 6, and 14 were 58.6, 65.9, and 68.7 percent respectively. Station 13 is significantly less than station 14 ($t = 1.79$, $t_{.95} = 1.66$) and is probably less than station 6 ($t = 1.48$, $t_{.92} = 1.43$). These indicated differences, although small, can be traced to local factors, the presence of a narrow bulldozed trail beside station 14, shown in Figure 2-6, and the erection of a tower at station 6 contrasted with the virtually undisturbed canopy near station 13. It does not therefore appear that serious cross-wind influences were affecting the entire array.

3.6 DOSAGE VERSUS DISTANCE ALONG WIND

The along-wind distribution can be divided into two sections, those observed above the canopy and those observed below the canopy. The following two sections describe variations along wind in these terms.

TABLE 3-6

OBSERVED DOSAGE FOR STATIONS 13, 6, AND 14 IN PERCENT OF ABOVE-CANOPY DOSAGE (LEVELS a, b, c, AND d ARE AT 6.5, 30, 56 AND 74 FT ABOVE GROUND)

Trial	Level	13	6	14
1	a	26.2	86.9	89.1
	b	37.5	97.7	77.6
	c	54.9	96.3	89.6
	d	53.9	97.5	64.9
2	a	17.2	30.5	9.7
	b	34.2	45.1	14.3
	c	69.9	65.5	27.3
	d	72.1	93.1	44.4
3	a	87.2	96.4	78.2
	b	105.5	90.4	115.0
	c	138.1	55.8	108.6
	d	140.2	85.6	117.3
4	a	29.5	49.8	67.3
	b	41.0	64.6	94.1
	c	46.9	70.2	92.8
	d	54.6	68.2	85.5
5	a	32.4	17.5	25.3
	b	33.8	18.4	27.4
	c	33.7	20.9	28.9
	d	36.6	21.2	29.1
6	a	26.5	48.3	39.3
	b	42.7	69.5	76.2
	c	50.9	77.7	78.3
	d	54.8	72.1	72.8
7	a	40.0	54.7	69.5
	b	55.0	72.0	108.2
	c	73.7	93.9	87.6
	d	79.2	81.0	100.0
8	a	60.1	46.5	46.0
	b	61.9	78.7	74.8
	c	82.5	73.9	85.0
	d	105.5	63.3	93.2
9	a	85.4	86.2	71.0
	b	83.1	69.3	74.5
	c	77.6	67.5	89.5
	d	84.3	77.1	129.6
10	a	33.6	35.0	24.7
	b	41.4	71.9	64.7
	c	33.3	82.0	93.2
	d	30.7	101.5	—
11	a	50.4	58.0	43.6
	b	53.0	57.7	46.6
	c	55.4	67.5	37.1
	d	63.0	68.4	31.2
12	a	112.5	27.0	65.0
	b	—	55.1	90.5
	c	43.8	76.9	108.4
	d	88.4	74.4	85.5
13	a	35.0	38.5	30.4
	b	43.7	54.4	59.2
	c	40.9	68.8	70.6
	d	37.3	84.8	72.6

3.6.1 Above Canopy Distribution

The above canopy distribution of dosage is analagous to the distribution of dosage near ground level from an elevated instantaneous line source. The important difference is that the top of the forest is not an impervious surface. Expressions for the distribution of dosage near ground level from a cross-wind, instantaneous infinite line source show a decrease of dosage with increasing distance, except for a short distance close to the source.

Although the theoretical expression is non-linear and even exhibits a maximum, over short distances like that of the present array it is often nearly linear.

Accordingly in the present analysis a linear model of the form

$$D = a + b x$$

was used in which x is the distance in hundreds of meters from an arbitrary axis 100 m north of the north tower. With this choice of axis, x is simply the station number since these range from 1 to 12 along the primary axis of the array and are spaced at 100 m intervals. It will be shown in Section 3.7 that dosage was rather uniform at the three top levels on the 200-ft towers. Consequently three points were available from stations 1 and 12, (146, 170, and 192 ft) and one from station 6, (140 ft) for inclusion in the analysis. The data are summarized in Table 3-7. Least squares methods were used to compute a and b for each of the 13 trials. For each trial the null hypothesis $b = 0$ was tested using the t-test.

The results of these computations for all 13 trials are summarized in Table 3-8. Values of a and b are given and computed values of "t" for testing the significance of b. It is evident from the table that trials, 1, 2, 6, 7, 10, 12, and 13 show a significant decrease of dosage with increasing distance, trial 3 shows a significant increase of dosage with increasing distance, and trials 4, 5, 8, 9, and 11 show no significant variation of dosage with distance from the source.

Figures 3-8, 3-9, and 3-10 present a comparison of the lines of best fit as observed, and the variation of 130 ft dosage versus distance as computed from Milly's expression (loc. cit.). In using the latter expression efficiencies of the disseminator and rotorods were assumed to be 35 and

TABLE 3-7

OBSERVED DOSAGES AT ABOVE-CANOPY LEVELS USED TO COMPUTE THE REGRESSION OF DOSAGE ON DISTANCE FROM SOURCE

Trial	Station One			Station Six	Station Twelve		
	146 ft	170 ft	192 ft	146 ft	146 ft	170 ft	192 ft
1	1701	1867	-	1521	1087	-	1107
2	3651	4168*	3904	3923	2736	2898	2984
3	1184	1202	1126	1200	1359	1575	1426
4	2191	2288	2236	1838	2431	2362	2269
5	6037	9117	11094	4061	5108	6309	7002
6	1779	1790	1647	1552	1275	1324	1301
7	1060	1166	1227	988	847	866	770
8	839	758	856	-	805	816	829
9	8141	8174*	8072	6888*	9473	8825	8156
10	11491	13075	12895	-	5791	5772	5654
11	9092	8928	9320	-	7314	9590	8580
12	18885	17938	16911	11133	10242	10888	9236
13	7668	7742	7778	-	3089	3578	3699

*Some FP counts were estimated from continuity considerations where rotorods were missing.

TABLE 3-8

THE COMPUTED VALUES OF a AND b IN THE EQUATION, $D = a + bx$, AND VALUES OF STUDENTS "t" TO TEST THE HYPOTHESIS, $b = 0$, FOR ABOVE-CANOPY DOSAGE (VALUES OF t, SIGNIFICANT AT THE 95% AND 99% LEVELS, ARE MARKED * AND ** RESPECTIVELY)

Trial	Computed a	Computed b	Degrees of Freedom	t
1	1857	- 62.6	3	- 9.50**
2	4079	- 95.2	5	- 4.70**
3	1129	25.9	5	4.10**
4	2156	11.6	5	0.80
5	8498	-239.0	5	- 1.69
6	1781	- 39.9	5	-10.20**
7	1178	- 29.4	5	- 6.30**
8	817	0.1	4	0.03
9	8259	- 1.8	5	- 0.03
10	13100	-613.0	4	-13.40**
11	9170	- 56.0	4	- 0.93
12	18108	-700.0	5	- 6.00**
13	8118	-389.0	4	-22.60**

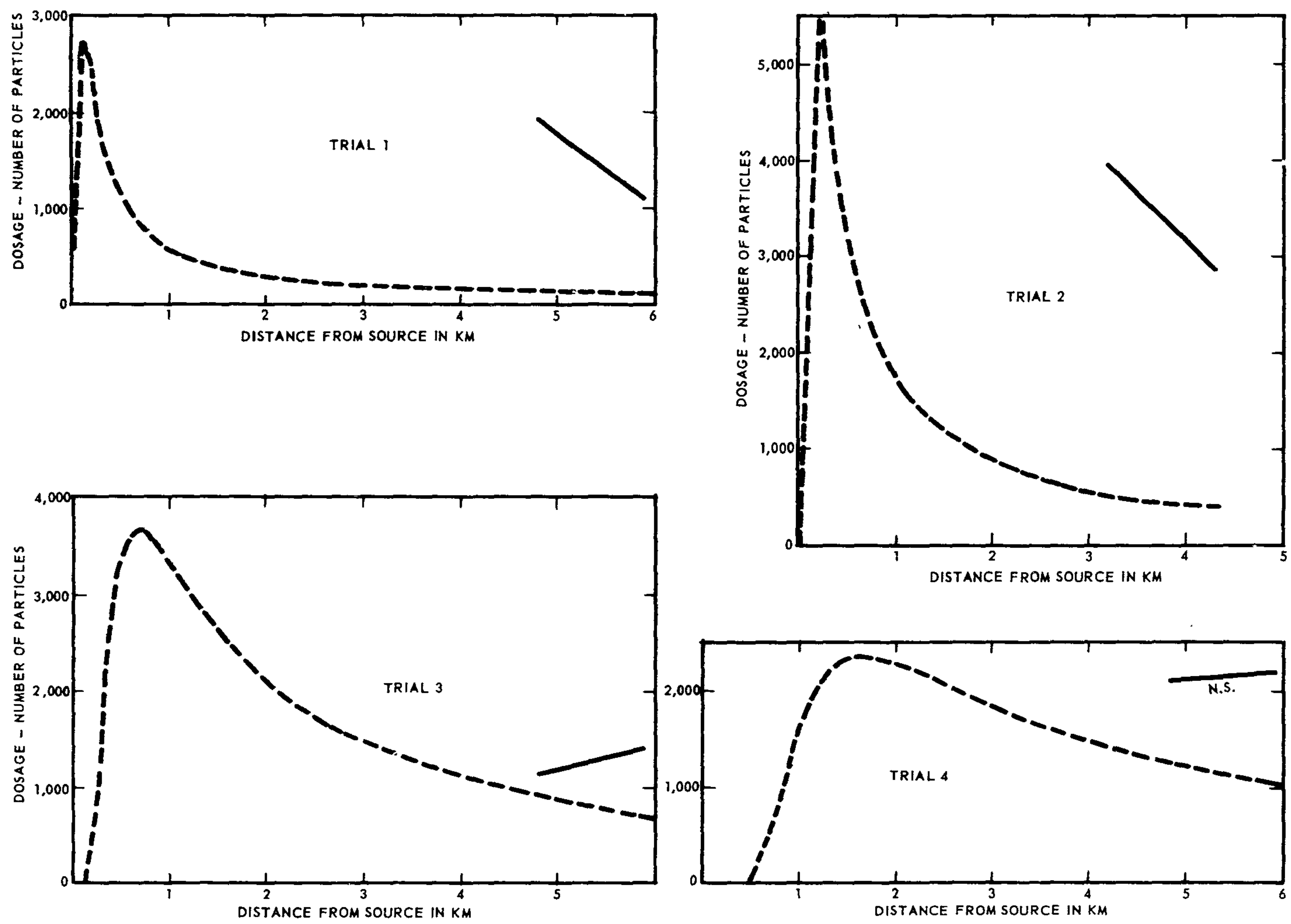


Figure 3-8 Above-Canopy FD Dosage Versus Distance, Trials 1, 2, 3 and 4. Dotted Line Computed, Solid Line Observed Line of Best Fit. (N. S. Indicates Slope Not Significant).

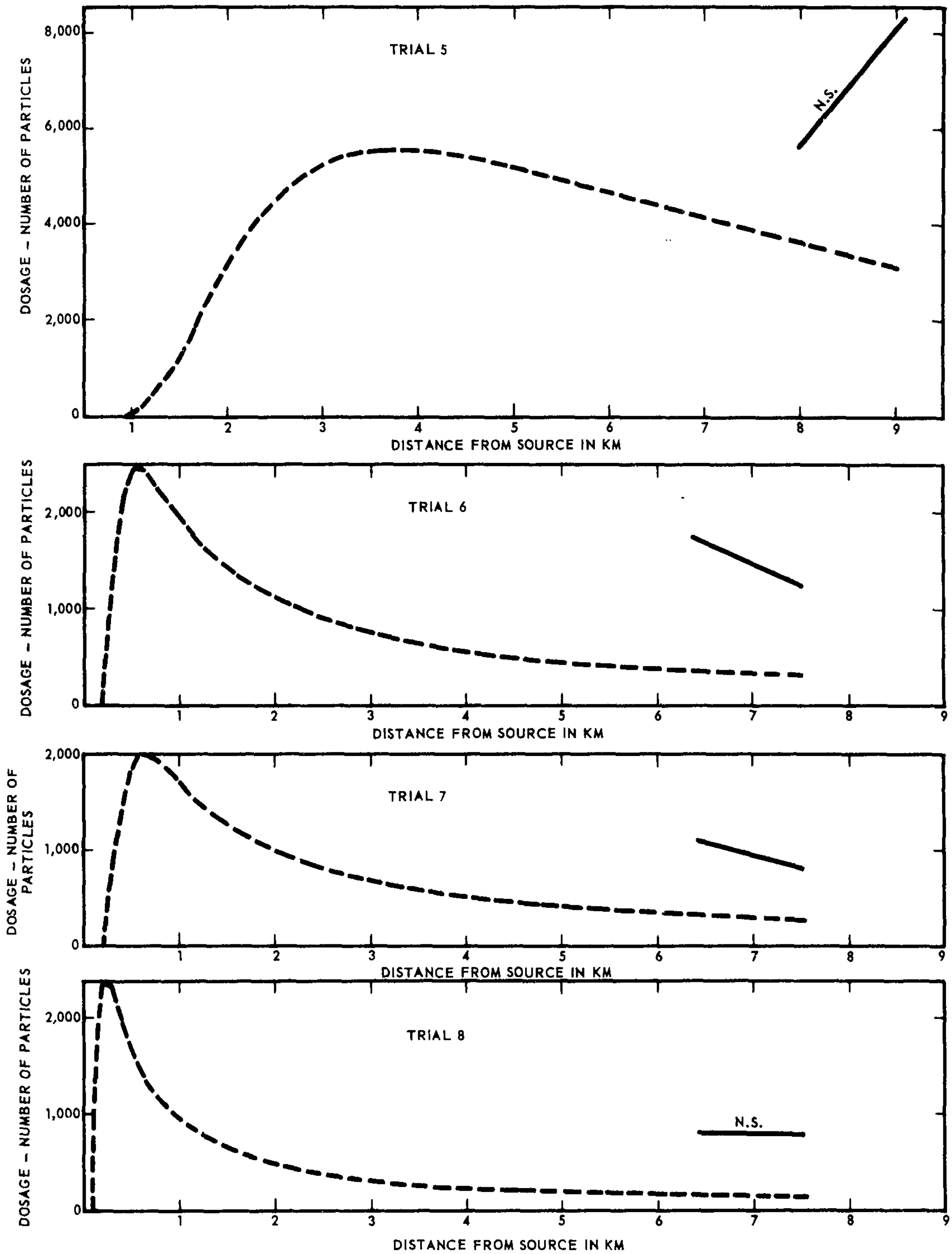


Figure 3-9 Above-canopy FP Dosage Versus Distance, Trials 5, 6, 7, and 8. Dotted Line Computed, Solid Line Observed Line of Best Fit. (N. S. Indicates Slope Not Significant).

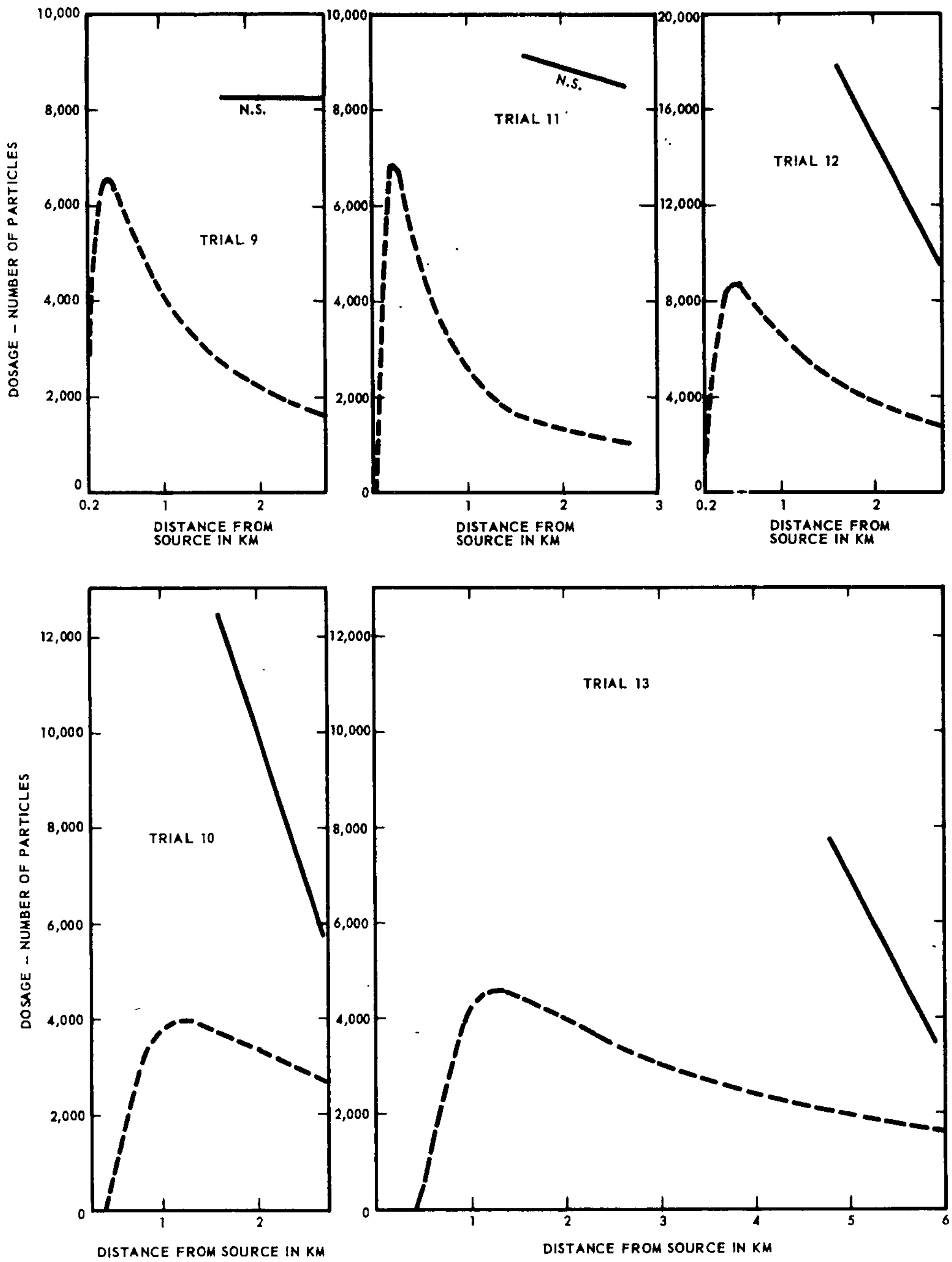


Figure 3-10 Above-Canopy FP Dosage, Trials 9, 10, 11, 12, and 13. Dotted Line Computed, Solid Line Observed Line of Best Fit. (N. S. Indicates Slope Not Significant)

50 percent respectively. It is to be noted that actual dosages are on the average about three and one half times the computed which suggests that greater efficiencies were realized. The touchdown points used in Section 3.4 are also shown in Figures 3-8, 3-9, and 3-10.

3.6.2 Below-Canopy Distribution

For purposes of analysis, the four lowest sampling levels, 6.5, 30, 56, and 74 ft are combined into a single number that is representative of below-canopy dosage. These data appear in Table 3-9. The observed variations of dosage with height through this layer are described separately in Section 3.7.

The treatment of the data is essentially the same as that described in Section 3.6.1 for above the canopy. A linear model of the form

$$D = a + b x$$

is again assumed where D is the average dosage for the four lowest levels at a distance x from an arbitrary zero 100 m north of the north tower. Since x is specified in hundreds of meters, x is in fact the station number. Stations 1 through 14 are used in obtaining least squares estimates of a and b for each of the trials, and as before Student's "t" is calculated to test the null hypothesis, b = 0. The results are summarized in Table 3-10 where trials 1, 2, 3, 10, 12, and 13 show a significant decrease of dosage with increasing distance, trial 4 shows a significant increase, and trials 5, 6, 7, 8, 9, and 11 show no significant variation of dosage with increasing distance.

In general the computed values of b in any one trial are similar above and below canopy, although there are some changes of sign when b is numerically small. Trial 5, however, which indicated a very large, although not significant, increase of above-canopy dosage with increasing distance shows only a very small increase (not significant) with distance below canopy.

A comparison of observed and computed below-canopy dosage versus distance is given in Figures 3-11, 3-12, and 3-13. The observed variation is represented by the regression lines and the computed variation is based on the Milly expression, again assuming disseminator and collector efficiencies of 35 and 50 percent respectively. It is to be noted that the presence

TABLE 3-9

OBSERVED AVERAGE DOSAGE AT FOUR BELOW-CANOPY LEVELS USED TO COMPUTE THE REGRESSION OF DOSAGE ON DISTANCE FROM SOURCE BY STATION

Trial	STATION NUMBER													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1813	1491	1246	618	1056	1387	1157	968	612	725	932	885	639	1190
2	3306	2012	2402	2189	1841	2053	2170	2413	1781	2113	1775	1452	1697	840
3	1174	890	1052	1098	963	1054	984	890	740	825	967	898	1513	1346
4	1722	1406	1432	1290	1389	1410	1446	1574	1556	1812	1654	1977	958	1895
5	1928	1946	1975	—	2073	1357	1529	1703	1770	1634	1722	2026	2375	1926
6	1272	1140	814	—	794	1031	1044	754	744	807	874	884	674	1028
7	914	916	—	697	698	755	701	823	501·	728	709	707	621	915
8	573	860	—	346	476	536	624	519	566	601	476	521	633	611
9	7757	6839	—	5745	7785	6186	8435	8517	8676	9386	7360	7345	6814	7518
10	9852	5112	4884	4328	4771	6838	5847	4088	5414	5292	3411	3104	3274	5737
11	5669	5923	7131	8213	7047	5537	5666	—	6332	5979	6786	6362	4882	3489
12	16434	13098	10567	12698	8306	8112	7206	6248	5752	6398	6601	7348	11343	12145
13	5754	5052	5585	5017	3979	3566	3875	3658	2856	1957	3541	2695	2270	3369

TABLE 3-10

THE COMPUTED VALUES OF a AND b IN THE EQUATION, $D = a + bx$, AND VALUES OF STUDENT'S t TO TEST THE HYPOTHESIS, $b = 0$ FOR BELOW-CANOPY DOSAGE (VALUES OF t, SIGNIFICANT AT THE 95% AND 99% LEVELS, ARE MARKED * AND ** RESPECTIVELY)

Trial	Computed a	Computed b	Degrees of Freedom	Computed t
1	1695	-112.2	12	-4.00**
2	2688	- 86.6	10	-2.89*
3	1098	- 21.0	10	-2.51*
4	1335	33.5	10	2.36*
5	1970	- 19.1	12	-0.88
6	1094	- 27.5	11	-2.06
7	872	- 19.0	11	-2.00
8	631	- 9.8	11	-0.95
9	6727	125.4	11	1.46
10	7000	-289.0	12	-2.33*
11	6102	- 3.8	11	-0.04
12	14278	-802.0	10	-5.20**
13	5639	-286.0	12	-4.70**

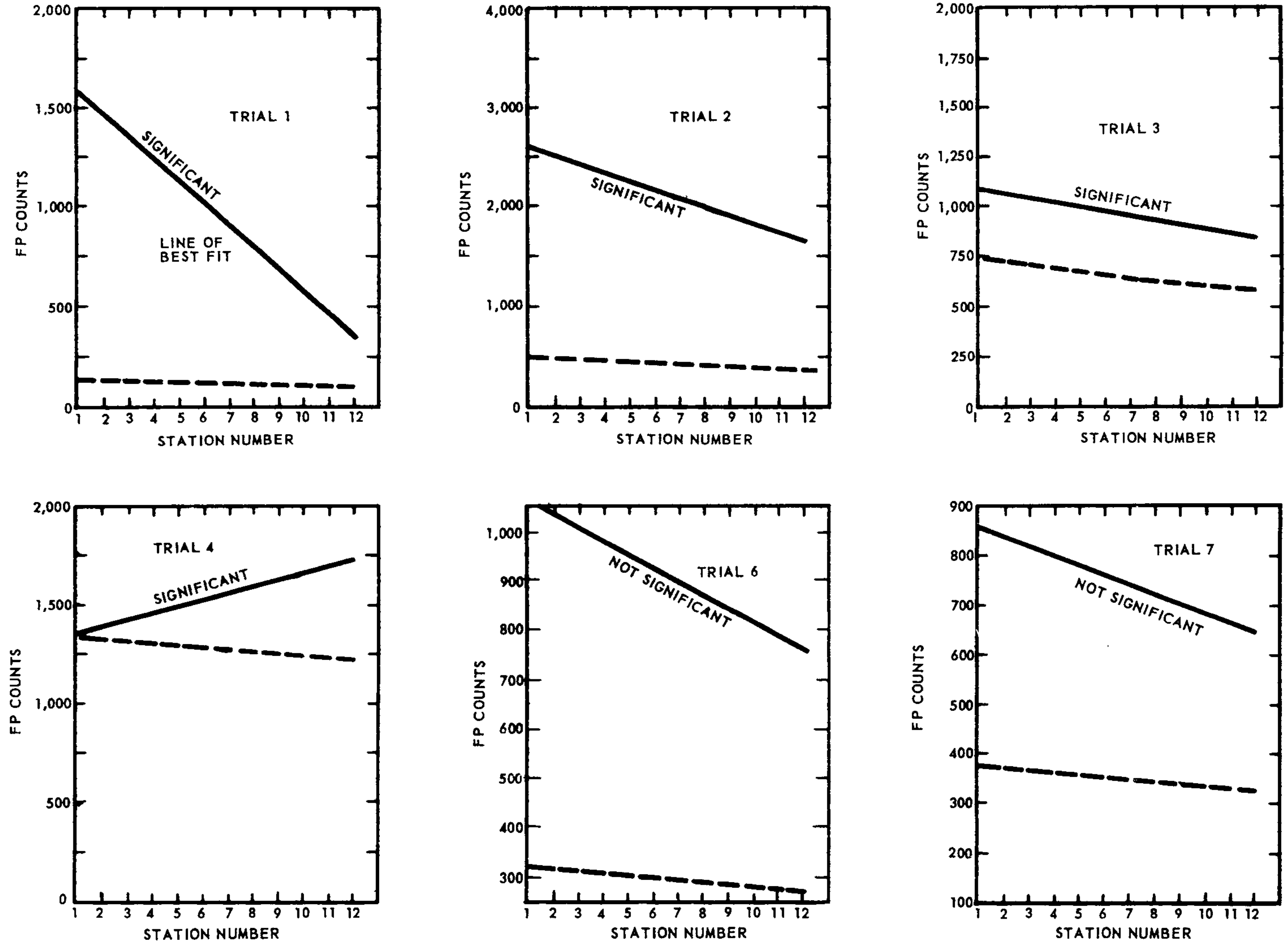


Figure 3-11. Below-Canopy Dosage Versus Station Number, Trials 1, 2, 3, 4, 6, 7. Dotted Line Computed for 6.5 ft, Solid Line Observed Line of Best Fit (Significance of Slope Indicated on Line)

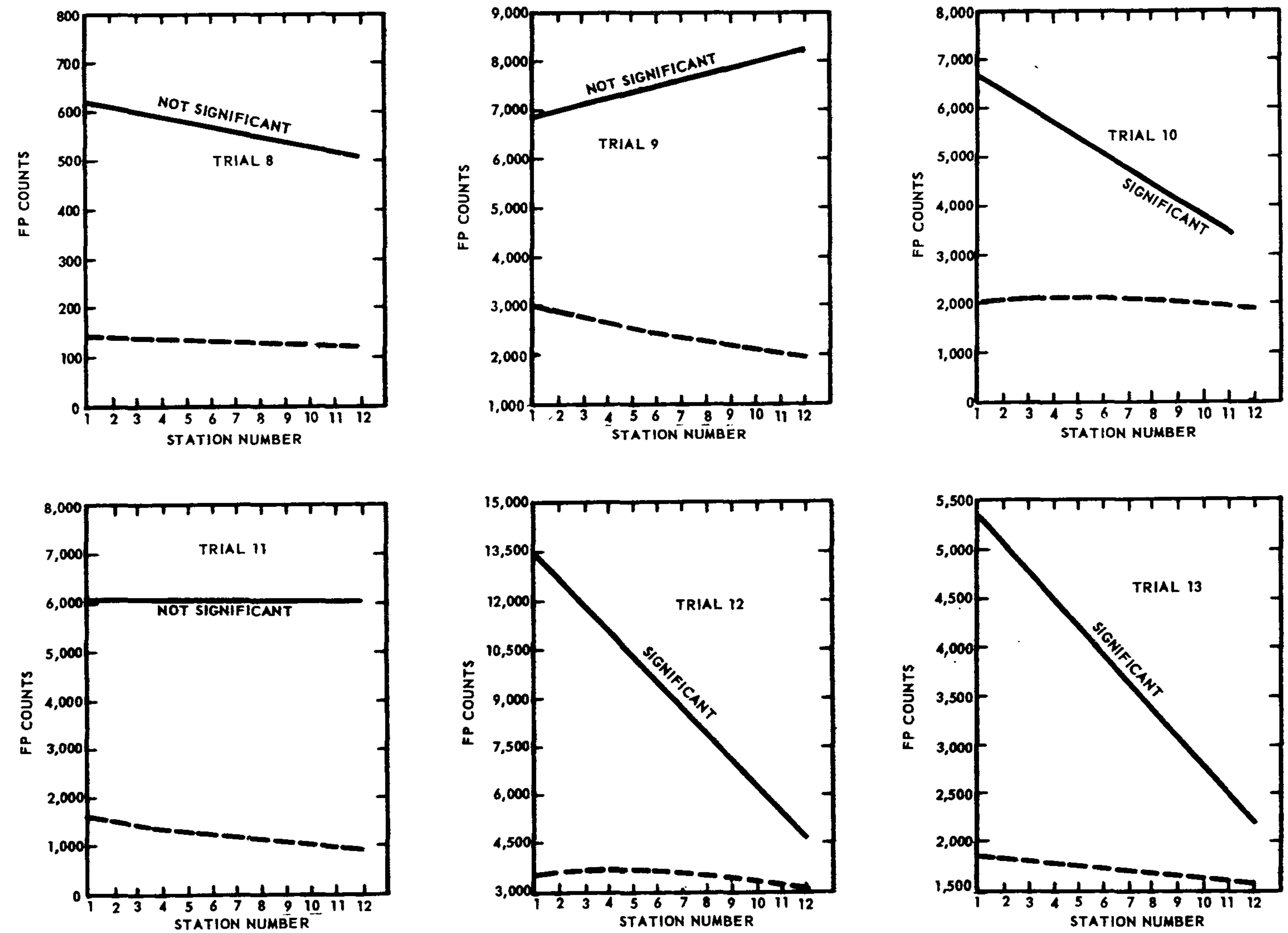


Figure 3-12 Below-Canopy Dosage Versus Station Number, Trials 8, 9, 10, 11, 12, 13. Dotted Line Computed for 6.5 ft, Solid Line Observed Line of Best Fit (Significance of Slope Indicated on Line)

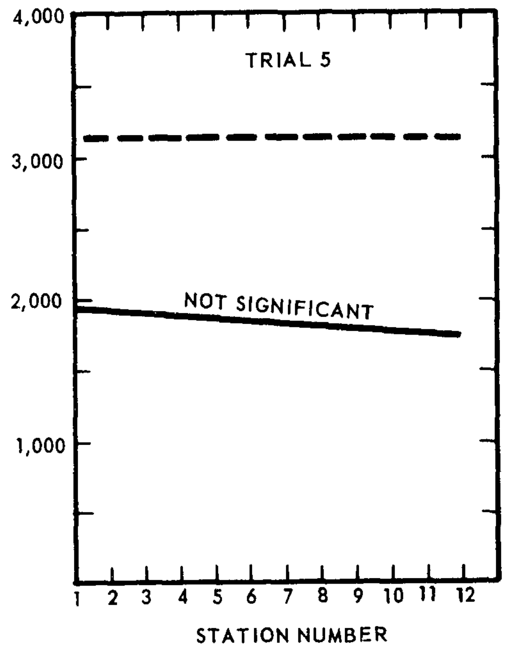


Figure 3-13 Below-Canopy Dosage Versus Station Number, Trial 5. Dotted Line Computed for 6.5 ft, Solid Line Observed Line of Best Fit (Significance of Slope Indicated on Line)

of the forest is completely disregarded in these computations. As a result the computations refer to a dosage whose duration lasts a few minutes rather than the few hours which actually occurred under the canopy.

As was noted above the canopy actual dosages are generally greater than the computed dosages. However it must be remembered that these comparisons do not apply to concentrations, which in some applications are more important than dosage. A more complete discussion of this subject appears in Section 5.7.

3.7 DOSAGE AS A FUNCTION OF HEIGHT

The variation of dosage with height can be studied within trials by computing an average dosage for each level in units of number-of-FP. Comparisons between trials, however, are then difficult to make because of

the tremendous differences in average dosage from trial to trial. To facilitate inter-trial comparisons, a normalizing procedure was adopted for expressing dosage at each height of each station as a percentage of the above-canopy dosage at that station. This procedure is first described and then the normalized profiles are presented for the 13 trials.

3.7.1 Normalizing Dosage

Dosage at each of the eight sampling heights can be expressed as a percentage of the above-canopy dosage which is defined as the average dosage observed at 146, 170, and 192 ft. In cases where significant dosage differences occur above the canopy, from one end of the array to the other, it is necessary to use different values of above-canopy dosage for each station.

The normalizing procedure was as follows.

1. Determine the basis of estimating above-canopy dosage at each station. If the variation above canopy were shown in Section 3.6.1 to be significant, the regression line was used, otherwise the mean value for the entire array was used.

2. Tabulate above-canopy dosage for each sampling station, a different number for each station* if from the regression line, or the same number if the mean were used.

3. Express the dosage at each level on each tower or tree as a percentage of the estimated above-canopy dosage.

Table 3-6 in Section 3.5 shows normalized dosages computed in this way for the four lowest levels of stations 13, 6, and 14 for all trials. Normalized dosages were computed for all levels of all stations and for all trials. In this way the 65 dosages observed during each trial at the 65 sampling points were converted to a common scale.

---

*Stations 13, 6, and 14 were computed from the same above-canopy dosage.

3.7.2 Normalized Profiles of Dosage Versus Height

The normalizing procedure described above yields, for each trial, 14 dosage values at the four lowest levels, three values at 146 ft, and two at 100, 170, and 192 ft. Mean values may be computed for each level and reasonable estimates of the standard deviation are possible at the four lowest levels. These quantities as computed for each trial are summarized in Table 3-11 and presented graphically in Figures 3-14, 3-15, and 3-16. The variation from station to station as shown in the table is consistently large in all trials except 5 where the variability is considerably less. Moreover the shape of the mean profile for trial 5, in Figure 3-16 is unlike the other twelve profiles. Trial 5 was exceptional in many respects but this is not surprising when it is recalled that it is the one trial carried out during southerly winds, whose speed and steadiness of direction were marginal insofar as the test criteria were concerned.

The 95 percent confidence interval for dosage is shown on the graphs of Figures 3-14, 3-15, and 3-16 to provide an indication of the kind of variability of dosage that one may reasonably expect from point to point under the canopy during any one trial.

The normalized data were also combined in the following ways to obtain profiles representative of average conditions. First, dosages from all 13 trials were combined. There were thus 182 dosages at the four lowest levels, 39 dosages at 146 ft, and 26 dosages at 100, 172, and 190 ft. Means and standard deviations were computed from which means and 95 percent confidence intervals are graphed in Figure 3-16. This provides a measure of variability that may be expected from point to point over the broad range of meteorological conditions encountered in the 13 trials. The same kind of computation was then repeated, first after removing trial 5, and secondly after removing trials 5, 9, and 11. The means and 95 percent confidence intervals are graphed in Figure 3-16 where it can be seen that the point to point variability is considerably reduced by the removal of the less typical meteorological conditions encountered during trials 5, 9, and 11. These were all night trials carried out under unusually light winds.

Finally, the mean dosages computed for each trial and summarized in Table 3-11 were themselves averaged for the 13 trials, and standard deviations were computed from which the mean profile and 95 percent confidence interval were graphed in Figure 3-16. A distinction must be made

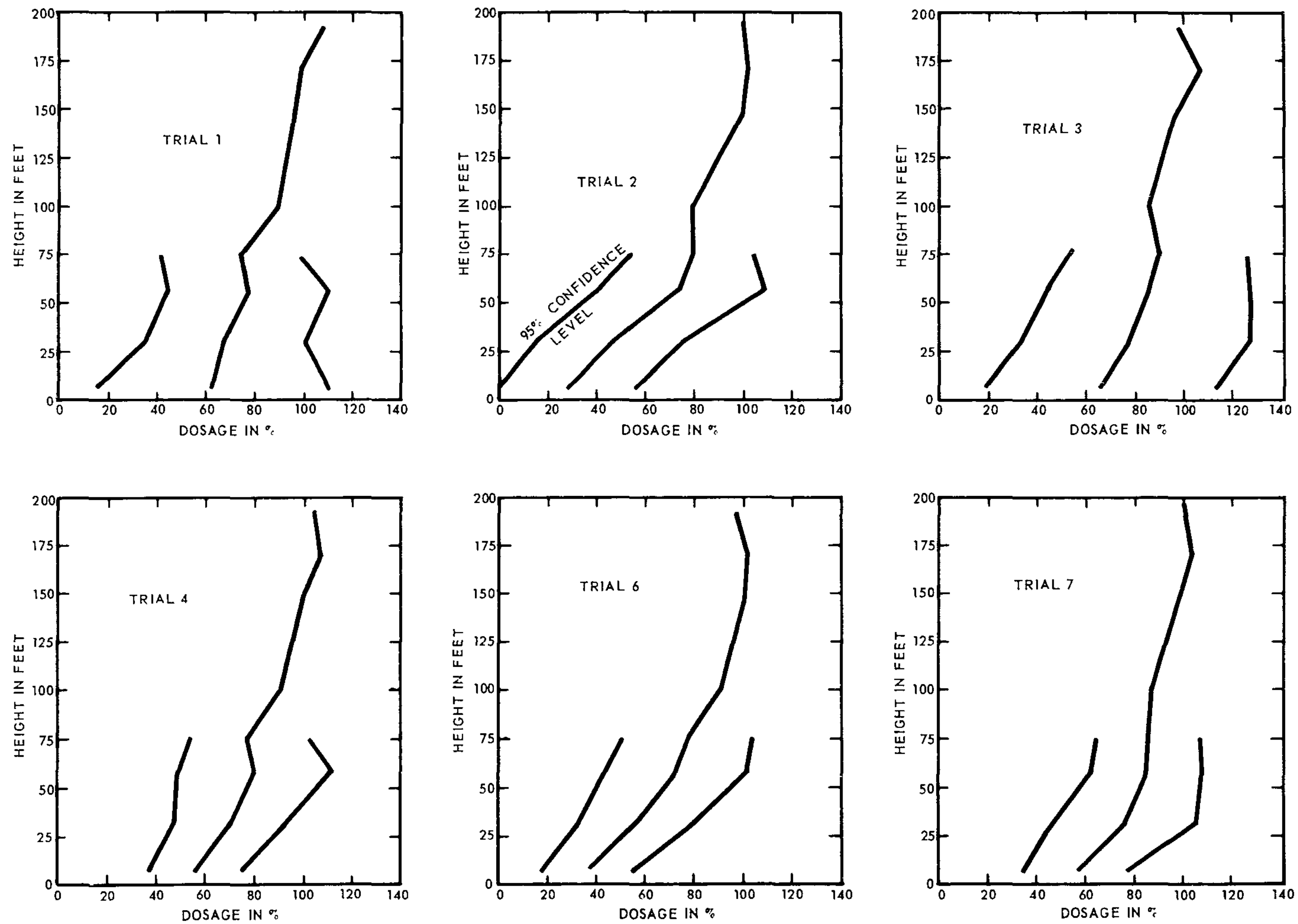


Figure 3-14 Vertical Profiles of Mean Dosage and of 95 Percent Confidence Intervals, by Trials (Dosage Expressed as a Percentage of Mean Above-Canopy Dosage)

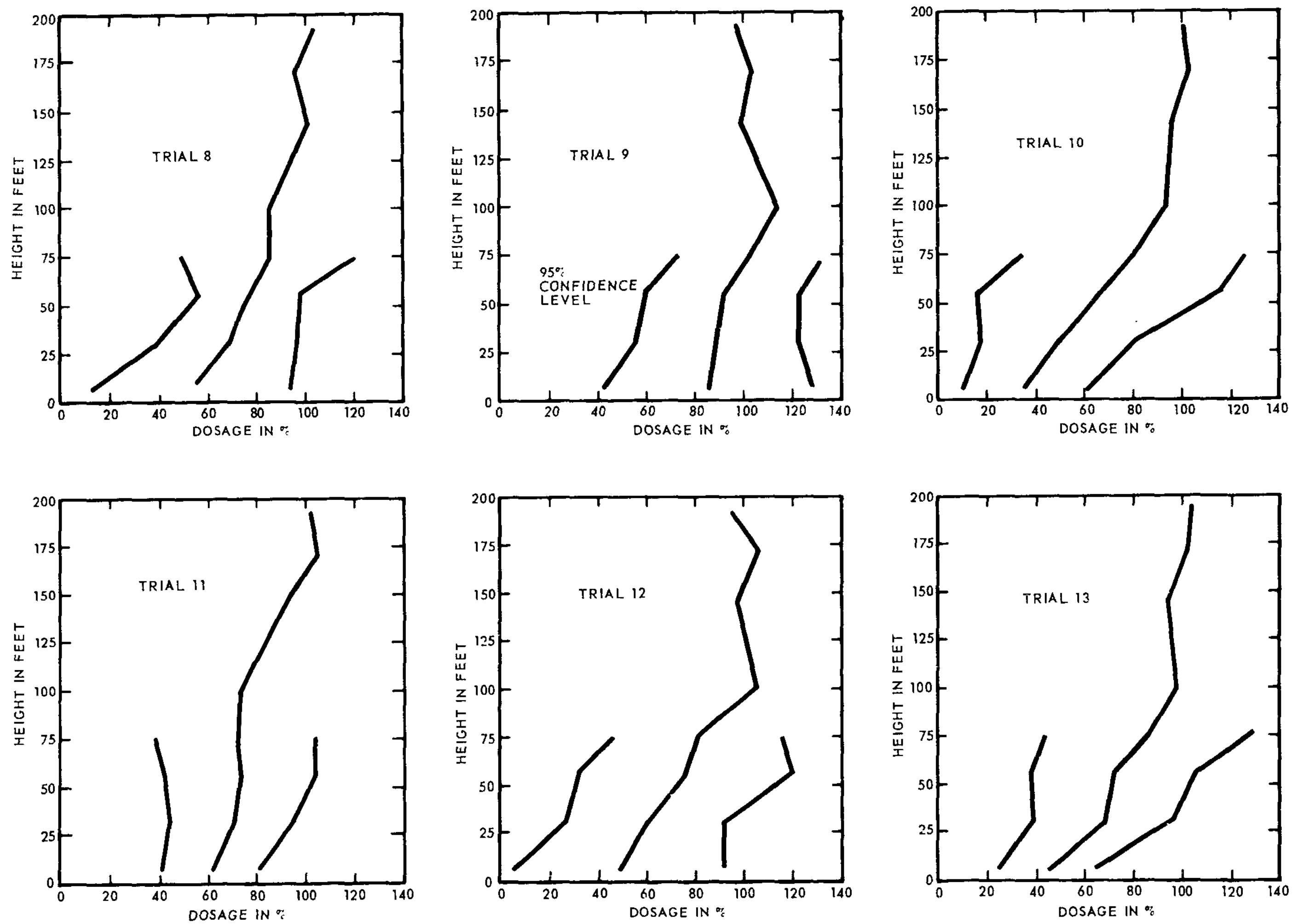


Figure 3-15 Vertical Profiles of Mean Dosage and of 95 Percent Confidence Intervals, by Trials (Dosage Expressed as a Percentage of Mean Above-Canopy Dosage)

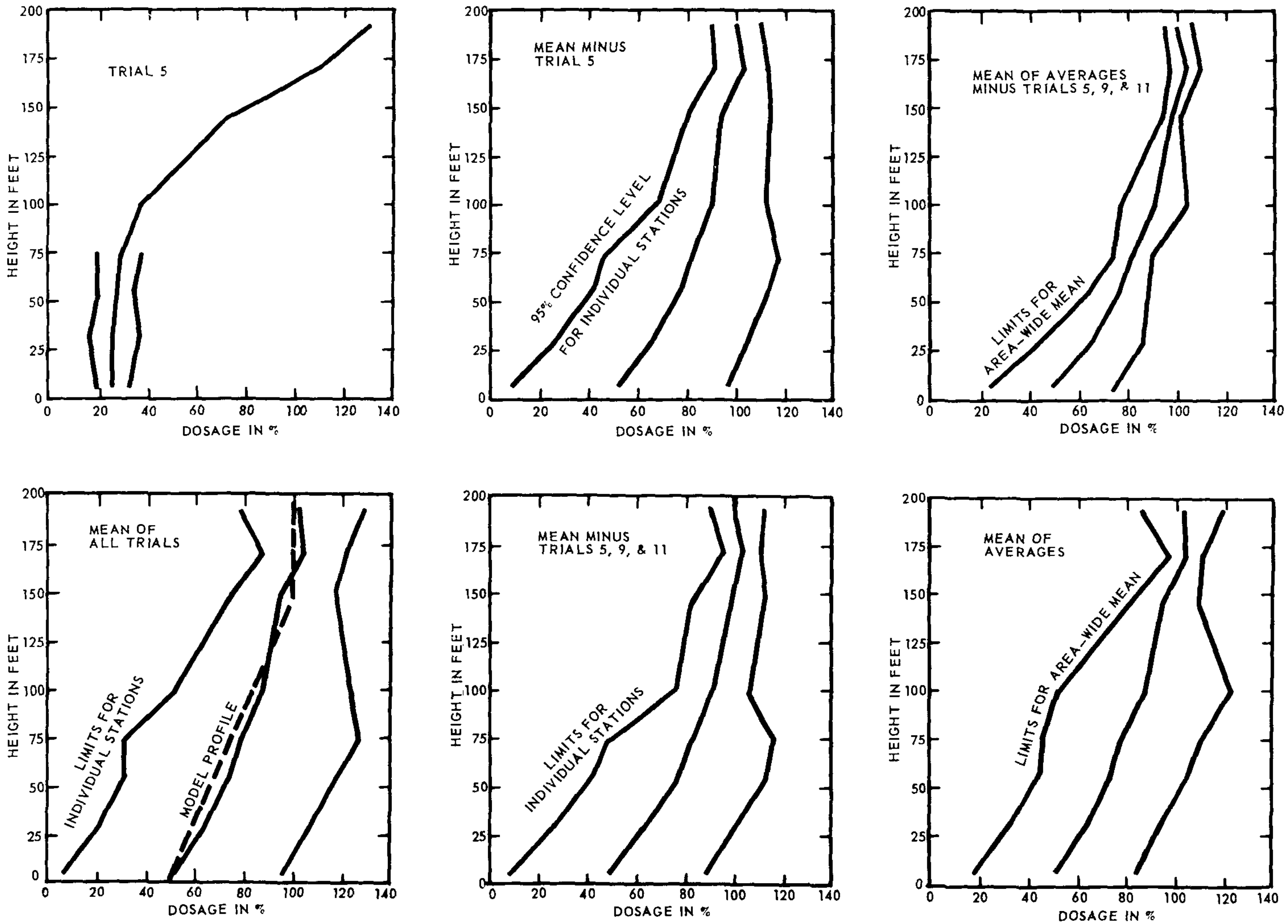


Figure 3-16 Vertical Profiles of Mean Dosage and Confidence Limits, Dosage Expressed as a Percentage of Mean Above-Canopy Dosage, Smaller Limits are Area-Wide, Larger Limits Refer to Inter-Station Visibility

I

TABLE 3-11

MEAN OF DOSAGE GIVEN BY LEVEL FOR EACH TRIAL AND EXPRESSED AS A PERCENTAGE OF ABOVE-CANOPY DOSAGE WITH THE ASSOCIATED STANDARD DEVIATION (MEAN IN UPPER LINE)

Trial	Height Above Ground							
	6.5	30	56	74	100	146	170	192
1	64.82 25.23	70.42 17.10	79.77 16.39	77.22 16.59	91.71	98.15	101.29	110.47
2	27.71 13.82	47.22 14.43	73.91 17.22	79.02 12.47	78.52	98.91	101.68	99.83
3	66.05 23.39	79.43 22.92	85.38 20.36	89.19 18.20	86.18	96.74	106.65	98.23
4	54.89 9.44	68.37 11.27	77.64 16.12	74.75 16.14	88.67	96.53	104.22	100.98
5	25.10 3.50	25.76 5.10	26.82 3.60	28.25 4.38	36.44	72.82	110.80	129.98
6	35.99 9.25	55.67 11.67	71.81 14.41	77.40 13.15	90.56	100.29	102.28	97.28
7	56.61 10.84	76.40 15.01	84.97 11.41	86.24 10.44	87.06	97.84	103.20	100.06
8	53.14 20.19	67.54 14.02	76.87 10.43	85.02 12.66	85.11	100.59	96.31	103.10
9	85.03 21.42	88.74 16.68	90.93 16.01	102.28 14.86	113.76	99.03	103.06	98.38
10	35.33 12.67	48.63 15.89	65.72 24.74	79.86 23.03	92.86	96.46	102.64	100.91
11	61.72 10.09	69.64 13.04	73.18 15.47	71.61 16.26	73.99	93.17	105.16	101.66
12	50.13 22.04	60.68 16.46	77.55 22.71	82.03 18.22	106.01	98.04	107.64	96.17
13	44.91 10.00	67.66 14.35	71.89 17.18	86.03 21.01	98.34	94.30	101.86	103.04

between this graph and the similar one using the original normalized data. The numbers used here in computing means are trial averages over the whole array. Consequently the confidence interval portrays the variability of the array average over a range of meteorological conditions, not the point-to-point variability shown in the other similar graph. The mean profiles are of course the same in the two graphs. The effect of removing trials 5, 9, and 11 from the variability of the array is also portrayed graphically in Figure 3-16 where the confidence interval appears to be considerably shrunk by eliminating the extreme meteorological situations. The data for these average profiles appear in Table 3-12.

The following model profile of dosage is suggested on the basis of the average of all trials:

> Dosage uniformly 100 percent from 200 ft to 140 ft.
>
> Dosage decreasing linearly from 140 ft to a value of 50 percent at the surface.

The model profile is shown in Figure 3-16.

TABLE 3-12

MEAN DOSAGE BY LEVELS AND ASSOCIATED STANDARD DEVIATIONS BASED ON (a) NORMALIZED DATA FOR ALL TRIALS, (b) ALL TRIALS EXCEPT 5, 9, AND 11, (c) ALL TRIALS EXCEPT 5, (d) AVERAGES FROM TABLE 4-10, FOR ALL TRIALS, AND (e) FOR ALL TRIALS EXCEPT 5, 9, AND 11 (MEAN IN UPPER LINE)

	Height Above Ground (Feet)							
	6.5	30	36	74	100	146	170	192
All Trials	50.81 22.94	63.66 21.61	73.73 22.34	78.44 22.63	86.86 18.32	95.54 11.03	103.60 7.14	103.15 12.41
Minus 5, 9, & 11	48.97 20.81	64.33 18.80	76.64 18.59	81.64 17.30	90.50 7.95	97.86 7.25	102.78 4.07	101.09 5.77
Minus 5	52.86 22.59	66.74 19.43	77.51 18.48	82.50 18.22	91.06 11.53	97.68 8.22	103.00 4.09	100.91 5.47
Mean of Averages all Trials	50.88 16.32	63.55 15.64	73.57 14.95	78.38 16.27	86.86 17.72	95.60 6.89	103.60 3.39	103.08 8.48
Mean of Averages Minus 5, 9, 11	48.96 12.16	64.20 10.37	76.55 5.74	81.68 4.52	90.50 7.18	97.78 1.79	102.78 2.95	101.01 3.81

SECTION 4

A PHYSICAL DESCRIPTION OF DIFFUSION

A complete account is given in Section 3 of the observed distribution of FP in 13 trials. In the course of the presentation of the data certain patterns were seen that were common to all trials. Certain differences were also observed. A mechanism will now be proposed, in qualitative terms, which interprets these common patterns and attributes the observed differences to meteorological variations. This will be followed in Section 5 by a mathematical modelling of the mechanism described below.

The cloud of FP originates effectively as an instantaneous, infinite line source. It moves toward the test array, with the above-canopy wind, as an expanding cylinder which eventually impinges upon the top of the forest. A steep downward gradient of FP is thereby produced within the forest as shown by the concentration versus height profiles for interval 5 in Figures 3-1, 3-2, and 3-3. Turbulent diffusion in combination with the gradient produces a rapid downward flux as shown by the appearance of FP at 6.5 ft within 30 minutes of its release, and the occurrence of the maximum at 6.5 ft only 30 minutes later than the maximum above the canopy. It is clear that gravitational settling is not responsible for this, since FP settles at a rate of only 9 ft/hr as pointed out in Section 2. The cloud of FP above the canopy continues downwind creating an extensive, secondary source within the forest and also undergoing a steady depletion because the top of the forest is not an impervious surface.

The emphasis rapidly shifts to the secondary volume source within the forest. Immediately after the passage of the cylindrical source cloud the gradient of FP concentration within the forest begins to reverse as shown in Figures 3-1, 3-2, and 3-3, and is soon directed upward. At the same time it is noticed, in Figures 3-4 and 3-5 that the concentration at 6.5 ft diminishes, at a rate which ranges from rapidly in trials 1 and 2 to very slowly in trials 9 and 11. It is clear that some variable factors, hence meteorological factors, are important to the decrease of the FP concentration.

Two processes appear to contribute to reducing the amount of FP in the forest. The first and more important is turbulent diffusion which produces a flux out the top of the forest as a result of the upward directed gradient. Once out of the forest the FP is either carried away horizontally by the mean wind or is transported upward by mechanical and thermal turbulence. This process is most vigorous on windy days (i. e. trials 1 and 2) and least vigorous on calm nights (i. e. trials 5, 9, and 11). The second process is gravitational settling which is a constant factor related to the settling rate of FP and density of the forest. It is likely to be a slow process since the Stokes' settling rate is only 9 ft/hr. There is evidence that this process can be detected when turbulent diffusion is slight, for if one examines the concentration profiles for trials 5, 9 and 11 in Figures 3-1, 3-2 and 3-3 it is seen that concentration decreases below 100 ft without the presence of a strong upward gradient.

Advection has been examined in Section 3.4 and shown to be unimportant.

A two-phase mechanism is thus proposed. Phase one covers the creation within the forest of a secondary source whose strength must be predicted. Phase two covers the weakening of the secondary source whose rate of weakening must be predicted. Account must also be taken of the possible attenuation of the primary cloud due to the non-impervious nature of the top of the canopy.

SECTION 5

A MATHEMATICAL MODEL OF THE DIFFUSION PROCESSES

The physical processes of diffusion above, through, and below the forest canopy have been described in qualitative terms in Section 4. It remains to give quantitative expression to these processes in the form of a mathematical model. This section describes the development of a mathematical model which takes into account the roles of meteorology and gravitational settling in the penetration phase of the problem, and suggests a method for dealing with the attenuation of the original line source resulting from the penetration. The forms of the mathematical equations are first developed from theoretical considerations. The FP data and meteorological data collected in the field are then treated using least squares techniques to estimate the theoretically derived coefficients. Finally the model is tested and some suggestions for applying it to other forests are given.

5.1 CRITERIA FOR THE MATHEMATICAL MODEL

Some criteria for the mathematical model are discussed below:

1. The model must apply to ground level. Since the distribution of the tracer was studied at four levels below the canopy, no doubt a generalized model could be developed to handle any of these four levels or any in-between level. In fact the effort at formulation of a mathematical model has been restricted to the level 6.5 feet above the ground, both because it is simpler with this limitation and because the acid test of any model is its performance near ground level.

2. As a minimum requirement, the model must be able to predict total dosage. If it can also predict the duration of the fumigation or provide any details concerning the rise and fall of the concentration, this will enhance its usefulness.

3. The meteorological predictors should be quantities that can be determined with standard instruments, and skill in forecasting them should be easily acquired. Quantitative descriptors of the wind and temperature would be examples of suitable meteorological predictors whereas refractive index or potential gradient would be unsuitable, even if relevant.

4. The model should not be unnecessarily complicated either conceptually or to work with, although the complexity of the model will be in direct proportion to the complexity of the processes that are being modeled. Reasonable accuracy in applying the model should be possible with a slide rule or nomogram.

5.2 METHOD OF ATTACK

The minimum objective of the model is the prediction of ground level (i.e. 6.5 ft) dosage. For each of the 13 trials, mean dosage at 6.5 ft has been computed and expressed as a percentage of above-canopy dosage. Details appear in Section 3.7. The average of all trials gives a 6.5 ft dosage of about 50 percent; one might stop there and simply predict the value, 50 percent, for all trials. However, much of the trial-to-trial variability about this mean is caused by meteorological variations. Better predictions may therefore result from a direct attempt at describing dosage, D, as a function of a set of meteorological variables (X_1, X_2, X_3, ---). There are some difficulties in this approach however because large dosage may result from a large initial flux into the forest (i.e. vigorous turbulence) or a slow flux out of the forest (i.e. slight turbulence). Thus a model which takes into account the two phases of the problem is inherently more flexible.

Dosage may be specified if the complete function of concentration versus time is known or can be predicted. Sections 3.3 and 3.4 describe the observed variation of concentration with time at 6.5 ft. The growth and decline phases combine into a strongly skewed curve which suggests that growth and decline are influenced by different factors. This general observation is elaborated upon in Section 4 in terms of an initial penetration from the primary overhead source and the weakening of a secondary source within the forest. The concentration-versus-time curves of Section 3.3 show considerable variation from trial to trial both in the magnitude of the maximum half-hourly concentration and in the duration of the decline phase. It therefore seems appropriate to model the dosage by predicting separately the growth and decline phases. i.e., χ_{max} and the rate of decrease, and integrating the curve to get dosage.

5.3 DEFINITION OF THE CONCENTRATION-VERSUS-TIME CURVE

If dosage is to be arrived at by first predicting the shape of the concentration-versus-time curve, some decisions are needed on how to specify the curve. Normalized concentration versus-time curves are presented for all thirteen trials in Section 3-3, Figures 3-4 and 3-5. Referring again to these curves, it will be recalled that all of them were strongly skewed. In addition to this asymmetry, one other feature was substantially the same in all trials, namely the maximum concentration usually occurred during the second half-hour after release of the tracer. The two features differentiating the curves were the value of the maximum concentration and the rate of decrease of the concentration. Since these two quantities not only define the distinctive features of the concentration-versus-time curve, but also afford a means of treating separately the growth and decline portions of the curve, it was decided to base the model on the prediction of the maximum concentration and the rate of decrease of concentration.

The quantities used in defining peak concentration and rate of decrease are as follows.

1. Above-canopy or overhead dosage, D_o

   The quantity desired here is the dosage attributable to the passage overhead of the original source cloud, excluding any FP emanating from the forest after the passage of the cloud. This is a predictable quantity* and in the present experiment would include only the dosage occurring in intervals 5 and 6. Since levels f, g, and h (146, 170, and 192 ft) are above canopy, an expression for evaluating D_o is

$$D_o = \frac{1}{3}\left[\sum_{i=f,g,h} \sum_{j=5}^{6} \chi_{ij}\right] \qquad (5\text{-}1)$$

   where χ_{ij} means the average concentration for the test array at level i during interval j.

2. Maximum Half-hourly Concentration, χ_x

   This is simply the highest value among all the a-level (6.5 ft) FP counts and defines the highest point on the concentration-versus-time curve.

*The prediction of overhead dosage is discussed in Section 5.6.

3. Penetration ratio, R

A quantity which provides a measure of the extent of canopy penetration in any trial is the penetration ratio, R, defined by the expression

$$R = \frac{\chi_x}{D_o} \qquad (5\text{-}2)$$

4. Decline ratio or Rate of Decrease

During the decline phase of the fumigation the ratio χ_{x+i}/χ_{x+i+1} is a measure of concentration at any time. The symbol i identifies a specific sampling interval after occurrence of χ_x, hence $i \geq o$. This is simply the ratio between consecutive half-hourly concentrations and is always greater than one.

Clearly if the penetration ratio, R, and hence χ_x, can be predicted, and the decline ratio can be predicted, the concentration-versus-time curve will be well defined. The following section will describe the method of selection of meteorological predictors, will indicate the form in which they may be expected to appear, and will evaluate the coefficients from the field data.

5.4 THE SELECTION OF METEOROLOGICAL PREDICTORS

For both the penetration ratio and the decline ratio, theoretical justification will be presented for the choice of meteorological predictors, and the form in which the predictor appears in the mathematical model. Specific expressions will then be obtained using the techniques of regression analysis.

5.4.1 Predicting the Penetration Ratio

The quantity, χ_x, provides a measure of the total flux of FP down through the canopy in response to the overhead passage of the source cloud. The quantity χ_x is proportional to the downward gradient of concentration, grad χ, and to the conductivity, k of the forest-air system, so we may write

$$\chi_x \;\alpha\; k \text{ grad } \chi \qquad (5\text{-}3)$$

At the time of overhead passage of the cloud, when the ground level concentration is zero, the gradient may be expressed:

$$\text{grad}\ \chi = \frac{\Delta\chi}{\Delta Z} = \frac{\chi_o}{h} \qquad (5\text{-}4)$$

where χ_o is the overhead concentration and h is the height of the forest. Since χ_o is directly related to the overhead dosage D_o, we express the gradient as

$$\text{grad}\ \chi = C_1 \frac{D_o}{h} \qquad (5\text{-}5)$$

where C_1 is a proportionality factor which equates χ_o and D_o.

The conductivity of the forest-air system will be directly proportional to the eddy conductivity of the air, k_m, and inversely proportional to the vegetative density, d, of the forest. The form of d need not be specified since it will be combined with other constants. Hence k will take the form

$$k = C_2 \frac{k_m}{d} \qquad (5\text{-}6)$$

where C_2 is an arbitrary constant.

The eddy conductivity is related to the degree of turbulence which was estimated by two quantities. One was the ratio of the wind speeds at 146 and 200 ft. If k_m is large, this ratio must be large. In practice, gaps in the data made it impossible to base the model on this quantity or to evaluate it fully. The second measure of turbulence was σ_θ, the standard deviation of the wind direction at 200 ft on the north tower as measured by a Beckman and Whitley wind vane. Holland (2) pointed out that for $\sigma_\theta < 20^o$, σ_θ is proportional to the intensity of cross-wind turbulence. The large overshoot that the Beckman and Whitley vane exhibits at its natural frequency will lead to overestimates of σ_θ, which are unlikely to be large unless eddies of the natural frequency are prominent in the gust spectrum. Although no spectral analyses were performed on the Beckman and Whitley wind record, the useful results obtained from these estimates of σ_θ suggest that the overshoot factor was not serious. σ_θ was evaluated about a 5-minute running mean direction. Details of this procedure appear in Volume III Section 7 of this report. While there were gaps in the record of σ_θ due to the

failure of the tape recorder in the last 3 trials, a subroutine was developed relating σ_θ and θ_r, the range of wind direction as recorded on the strip chart. In this way σ_θ was computed for the missing data points and adopted as the measure of turbulence. A direct measure of the intensity of vertical turbulence at 200 ft was not available but it is approximately proportional to σ_θ when θ is averaged over periods short enough to eliminate meander.

Hence an expression for k_m becomes

$$k_m = C_3 \sigma_\theta \tag{5-7}$$

where C_3 is an arbitrary constant, and substituting from (5-7) in (5-6) yields

$$k = \frac{C_2 C_3}{d} \sigma_\theta \tag{5-8}$$

We may now substitute from (5-5) and (5-8) in 5-3 and obtain

$$\chi_x \quad \alpha \quad \frac{C_1 C_2 C_3}{h\, d} D_o \sigma_\theta \tag{5-9}$$

Replacing χ_x from (5-9) in (5-2) gives

$$R \quad \alpha \quad \frac{C_1 C_2 C_3}{d\, h} \sigma_{\theta}',$$

or combining all the constants,

$$R = b\, \sigma_\theta \tag{5-10}$$

A linear regression analysis of the thirteen trials, as described below provided an estimate of b.

The following procedure was used. For each of the thirteen trials, values of R and σ_θ were determined. The value of σ_θ was a mean for the intervals between the time of release of FP and the time of occurrence of χ_x. Hence for trial 1 when χ_x occurred in interval 5, σ_θ is the computed value for interval 5, whereas for trials 5 and 12, when χ_x occurred in interval 7, σ_θ is the mean of intervals 5, 6, and 7. For trials 11, 12, and 13 σ_θ was computed from θ_r, the range of θ as read from the strip chart,* because there was no magnetic tape record. σ_θ was also computed in the

*26 half-hourly periods from trials 1, 2, 6, 7, and 8 were analyzed using least squares methods to yield the following equation for predicting σ_θ:

$$\sigma_\theta = 5.5 + .34\, \theta_r, \quad \theta_r \text{ in chart units.}$$

The sample correlation coefficient between σ_θ and θ_r was 0.65 which is highly significant ($r_{.99} = 0.50$).

same way for trial 4 to replace an obviously erroneous value of σ_θ gained from the magnetic tape.

The raw data and computed quantities are given in Table 5-1 and plotted on Figure 5-1. The regression model used was for a straight line through the origin subject to the condition, standard deviation of Y, the dependent variable, is proportional to X, the independent variable. For this model Snedecor (3) gives

$$b = \frac{1}{n} \sum_{i=1}^{n} Y_i / X_i, \text{ and}$$

$$\hat{Y} = b\,X$$

where $\hat{Y}$ signifies a regression estimate of Y.

With R playing the role of Y and σ_θ the role of X it is evident from Figure 5-1 that the standard deviation of R increases with increasing σ_θ, hence the choice of this form for b. The analysis yields

$$b = 0.0176$$

and

$$\hat{R} = 0.0176\,\sigma_\theta \tag{5-11}$$

The t-test for significance of slope under the null hypothesis, $b \leq 0$, gives $t = 2.71$, (12 degrees of freedom) which indicates that the slope is highly significant.

The technique for using this relationship in the model will be described in Section 5.5. The method of predicting decrease rates will be described in Section 5.4.2.

5.4.2 Predicting the Decrease Rate

After the straight line cloud has blown overhead, a considerable quantity of the effluent remains behind in the forest. Thereafter the forest behaves as a secondary source whose rate of weakening must be predicted.

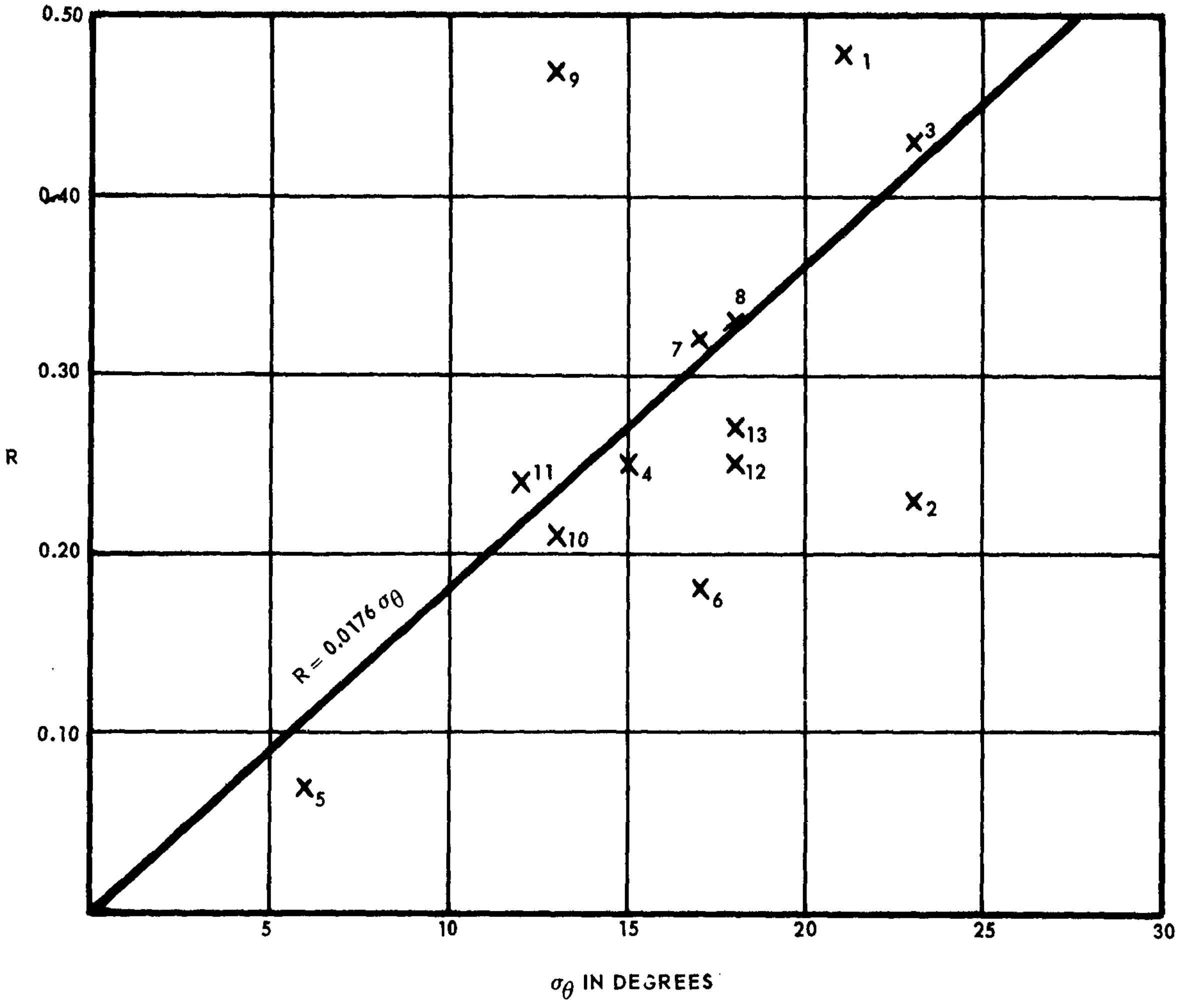


Figure 5-1 Penetration Ratio, R, Versus σ_θ
Numbers Beside Plots Identify Trial

TABLE 5-1

PREDICTION OF PENETRATION RATIO, R, FROM σ_{θ}

Trial	χ_x	D_o	R	σ_{θ}	$100\left(R/\sigma_{\theta}\right)$
1	727	1504	0.48	21	2.29
2	760	3325	0.23	23	1.00
3	528	1231	0.43	23	1.87
4	524	2093	0.25	15	1.67
5	533	7310	0.07	6	1.17
6	264	1478	0.18	17	1.06
7	299	935	0.32	17	1.88
8	255	762	0.33	18	1.83
9	3101	6648	0.47	13	3.62
10	1931	9022	0.21	13	1.62
11	1860	7604	0.24	12	2.00
12	3328	13199	0.25	18	1.39
13	1414	5266	0.27	18	1.50

$$b = 0.0176$$

$$\hat{R} = 0.0176\,\sigma_{\theta}$$

Consider a volume source whose strength we designate by χ, the concentration of material, at any instant of time. We seek an expression for $d\chi$, the change in χ in the time increment dt. During decrease, several factors in addition to the source strength contribute to $d\chi$ so we may write:

$$d\chi = d\chi_1 + d\chi_2 + d\chi_3 \qquad (5\text{-}12)$$

$d\chi_1$ = losses due gravitational settling.

= $-C_1 \chi\, dt$ where C_1 is an arbitrary constant.

$d\chi_2$ = losses due horizontal removal at top of the forest and vertical removal by mechanical turbulence

= $-C_2 U \chi\, dt$, where U is the 200-ft wind speed and C_2 is an arbitrary constant.

$d\chi_3$ = losses due transport upward by thermal turbulence, or inhibition of vertical removal by mechanical turbulence.

= $-C_3 \dfrac{dT}{dZ} \chi\, dt$

The quantity $\frac{dT}{dZ}$ should be the lapse rate through the first few hundred feet above the canopy but this was not measured. However it was noticed in analyzing lapse rates below the canopy that the extent of heating of the forest top was well differentiated by the strength of the inversion between 6 and 100 ft.* In other words,

$$\frac{dT}{dZ} \quad \alpha \quad \Delta T \text{ where } \Delta T = T_{100} - T_6$$

Therefore an approximate expression for $d\chi_3$ is

$$d\chi_3 = -C_4 \Delta T \chi\, dt$$

Combining the three components of $d\chi$ yields

$$d\chi = -(C_1 + C_2 U + C_4 \Delta T)\, \chi\, dt$$

which becomes, upon integrating and setting $\chi = \chi_x$ at $t = 0$.

*This is discussed in Section 2.2, Part II, Volume II of this report.

$$\chi = \chi_x e^{-(C_1 + C_2 U + C_4 \Delta T)t} \qquad (5\text{-}13)$$

Now suppose that χ_{x+i} and χ_{x+i+1} are the strengths of the source at i and i + 1 time increments after the occurrence of χ_x. (In this program the time increment was 30 minutes.) We may then write

$$\frac{\chi_{x+i}}{\chi_{x+i+1}} = \frac{e^{(C_1+C_2 U+C_4 \Delta T) \quad (i+1)}}{e^{(C_1+C_2U+C_4 \Delta T) \; i}}$$

or

$$\log_e\left(\frac{\chi_{x+i}}{\chi_{x+i+1}}\right) = C_1+C_2U+C_4 \Delta T \qquad (5\text{-}14)$$

Making the linear conversion to the logarithmic base, 10, and introducing new constants we obtain

$$\log_{10}\left(\frac{\chi_{x+i}}{\chi_{x+i+1}}\right) = b_o + b_1 U + b_2 \Delta T \qquad (5\text{-}15)$$

Equation (5-15) designates U and ΔT as predictors of the decline ratio and indicates the form in which they will appear due to the logarithmic nature of the decrease. It remains now to evaluate b_o, b_1, and b_2 from the data using linear least squares techniques.

However before plunging into the regression analysis the experimental data may be examined to determine if indeed the decrease of FP concentration appears to be exponential. Beginning with χ_x, the half hourly counts were plotted against time on semi-logarithmic paper. If U and ΔT were to remain constant thoughout the decrease, a straight line should result. Figure 5-2 gives decrease curves for trials 5, 7, 10, and 11 as typical examples. Trial 5 exhibits an inflection 3 intervals after the FP drop with nearly straight lines before and after the inflection, while the other trials approximate straight lines. The experimental evidence for an exponential decrease law is impressive.

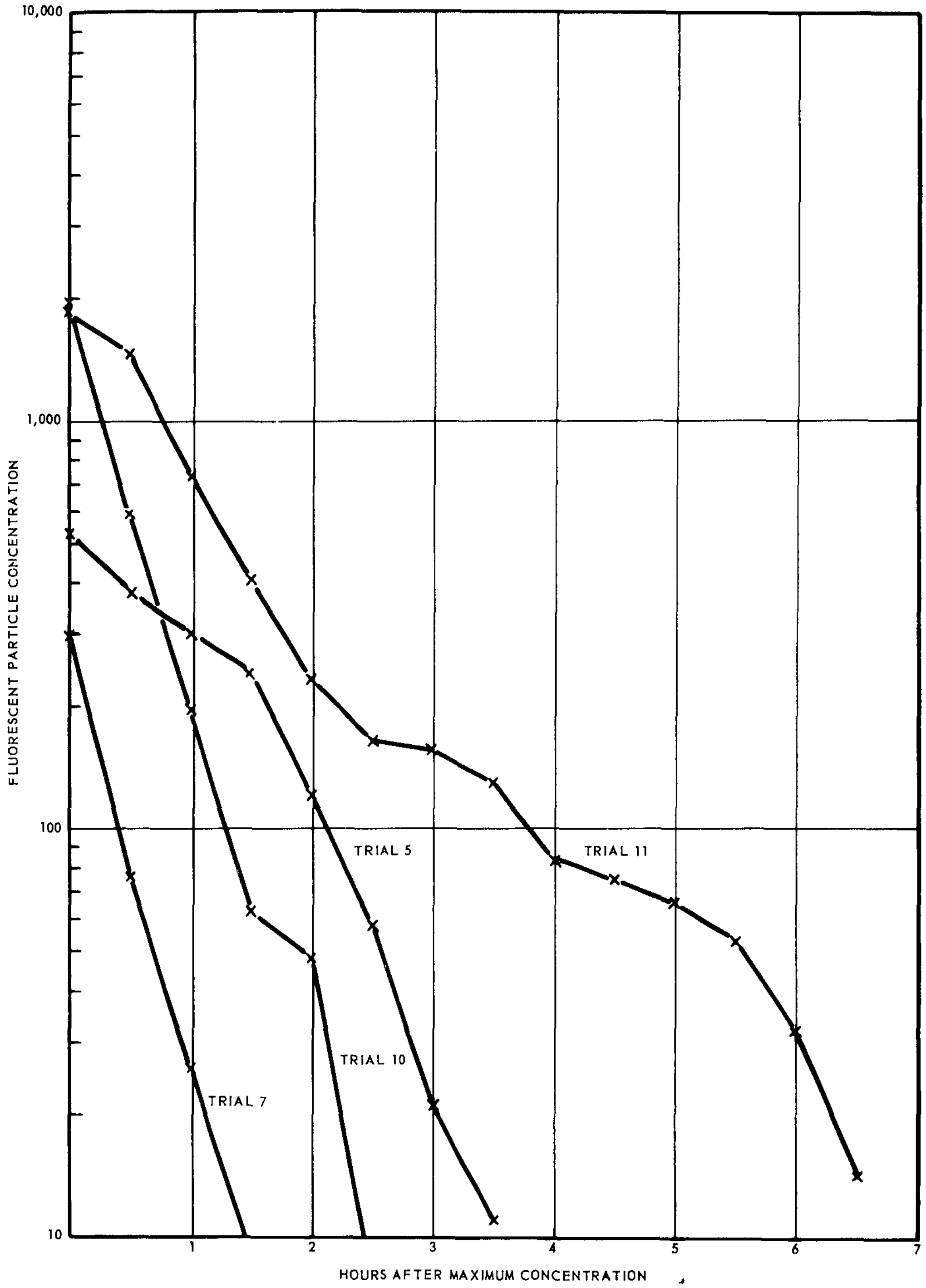


Figure 5-2 Concentration Decrease Curves for Trials 5, 7, 10, and 11

In approaching the regression analysis it may be noted that each pair of consecutive concentrations during decrease yields a set of values of the three variables, $\log_{10}\left(\frac{X_{x+i}}{X_{x+i+1}}\right)$, U, and ΔT. Since 13 points are scarcely adequate to estimate three regression constants, it was important to take some advantage of this feature. A procedure was followed which yielded a total of twenty-one points. Curves similar to those in Figure 5-2 were plotted for each trial. If a single straight line provided a good fit to the consecutive concentrations, a single average value of $\log_{10}\left(\frac{X_{x+i}}{X_{x+i+1}}\right)$ was computed and tabulated with average values of U and ΔT for the total time interval. If the decrease seemed to be defined by two or more well defined straight line segments, two or more points were provided for the analysis. Table 5-2 contains the raw data in a form that identifies the trial and intervals for which they apply. Standard linear, least squares techniques were applied to the data to yield the following estimates of the regression coefficients:

$$b_o = 0.161$$

$$b_1 = 0.019$$

$$b_2 = 0.013$$

and the regression equation

$$\log_{10}\left(\frac{X_{x+i}}{X_{x+i+1}}\right) = 0.161 + 0.019\ U + 0.013\ \Delta T \qquad (5\text{-}16)$$

The simple correlation coefficients between predictand and predictors are 0.68 and 0.70 both of which are highly significants ($r_{.99} = 0.55$). The multiple correlation coefficient is 0.79 which is also highly significant ($R_{.99} = 0.63$).

The combination of this expression with equation (5-11) into a mathematical model is described in Section 5.5.

TABLE 5-2

VALUES OF $Y = \log_{10}\left(\frac{\chi_{x+i}}{\chi_{x+i+1}}\right)$, U, AND ΔT OBTAINED IN THIRTEEN TRIALS, AND PRINCIPAL RESULTS OF A LEAST SQUARES ANALYSIS OF THESE DATA. (U in mi/hr, ΔT in tenths deg C)

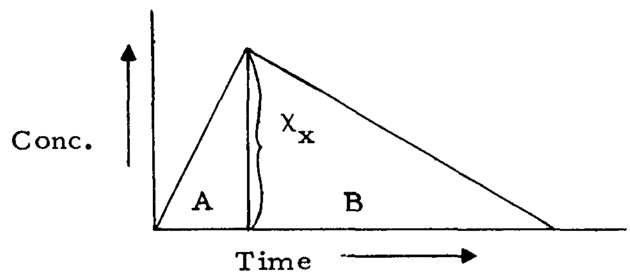
Trial	First Interval	No. of Intervals	Y	U	ΔT
1	5	1	0.46	14	17
2	6	2	0.74	13	14
3	6	3	0.53	10	15
4	6	5	0.33	10	5
5	7	3	0.17	6	-2
5	10	4	0.34	7	-2
6	6	2	0.43	12	8
6	8	3	0.36	7	6
7	6	3	0.51	11	2
8	6	3	0.54	13	0
9	6	9	0.21	4	-2
9	15	5	0.12	3	-2
10	6	5	0.28	9	4
11	6	5	0.21	5	0
11	11	6	0.08	4	-3
11	17	3	0.26	4	-4
11	6	14	0.17	4	-2
12	7	4	0.53	3	9
12	11	2	0.26	4	8
12	6	5	0.44	9	3

$r_{Y,U} = .68$, $r_{Y,\Delta T} = .70$, Multiple corr. coeff. = .79

$b_o = .161$, $b_1 = .0193$, $b_2 = .0127$

5.5 EXPRESSION FOR DOSAGE PREDICTION

The sketch below presents a schematic curve of concentration versus time. A is that portion of the dosage occurring up to and including the peak half hour, and B is that portion occurring during the decrease. We know that, on the average, χ_x occurs in the second half hour after the drop, and we have expressions for predicting χ_x and the rate of decrease. We wish now to combine this information into a prediction of D_{gr}, the ground-level dosage.



Clearly, from the above sketch

$$D_{gr} = A + B \tag{5-17}$$

Most of A occurs during the peak half hour as indicated in Table 3-4 and on the average it was found that

$$A = 1.23\ \chi_x$$

But since $\chi_x = RD_o$ from (5-2), and (5-11) provides a means of estimating R, we obtain as estimates of χ_x and A

$$\chi_x = 0.0176\ \sigma_\theta D_o \tag{5-18}$$

$$A = 0.0216\ \sigma_\theta D_o \tag{5-19}$$

As a starting point for estimating B we can express it as the sum of all the half hourly mean concentrations after χ_x; thus

$$B = \sum_{i=1}^{\infty} \chi_{x+i} \qquad (5\text{-}20)$$

The decrease of χ has been described in Equation (5-16) as

$$\log_{10}\left(\frac{\chi_{x+i}}{\chi_{x+i+1}}\right) = 0.161 + 0.019U + 0.013\ \Delta T$$

which may also be written as

$$\chi_{x+i+1} = \chi_{x+i}\ 10^{-(0.161 + 0.019U + 0.013\ \Delta T)} \qquad (5\text{-}21)$$

To simplify the notation, let $m = 0.161 + 0.019U + 0.013\ \Delta T$, and rewrite Equation (5-21) as

$$\chi_{x+i+1} = \chi_{x+i}\ 10^{-m} \qquad (5\text{-}22)$$

Then

$$\chi_{x+1} = \chi_x\ 10^{-m}$$

$$\chi_{x+2} = \chi_{x+1}\ 10^{-m} = \chi_x\ 10^{-2m}$$

$$\chi_{x+3} = \chi_{x+2}\ 10^{-m} = \chi_x\ 10^{-3m}$$

or, in general, $\chi_{x+k} = \chi_x\ 10^{-km}$,

so that substituting in Equation (5-20) we get

$$B = \chi_x \left\{ \frac{1}{10^m} + \frac{1}{10^{2m}} + \ldots \right\}$$

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The quantity inside the braces is a convergent series which may be evaluated by the methods of finite differences. In fact

$$\frac{1}{10^m} + \frac{1}{10^{2m}} + \ldots = \sum_{y=1}^{\infty} \frac{1}{10^{ym}} = \frac{1}{10^m - 1}$$

Accordingly we may write

$$B = \frac{X_x}{10^m - 1}$$

and substituting for X_x from Equation (5-18) gives

$$B = \frac{0.0176\ \sigma_\theta D_o}{(10^m - 1)} \qquad (5\text{-}23)$$

Finally, if we combine the expressions for A (Equation 5-19) and B (Equation 5-23), the expression for dosage becomes

$$D_{gr} = \left[0.0216 + \frac{0.0176}{(10^m - 1)}\right] \sigma_\theta D_o$$

As a working equation we must replace m and get

$$D_{gr} = \left[0.0216 + \frac{0.0176}{(10^{0.161 + 0.019U + 0.013\ \Delta T} - 1)}\right] \sigma_\theta D_o$$

(5-24)

Equation (5-24) is the mathematical model for predicting ground-level dosage when above canopy dosage is known. When it is not known Equation (5-24) may be modified to yield

$$R_D = \frac{D_{gr}}{D_o} = 0.0216 + \left[\frac{0.0176}{(10^{0.161 + 0.019U + 0.013\,\Delta T} - 1)}\right]^{\sigma}\theta \qquad (5\text{-}25)$$

for predicting relative ground-level dosage.

5.5.1 Predicting Time for Decrease to a Critical Concentration

We recall that

$$\chi_{x+k} = \chi_x 10^{-km}$$

where k = number of half hours after the occurrence of χ_x. Now if we let

$$\chi_{x+k} = \chi_{crit}$$

where χ_{crit} is some critical value of the concentration, we can write

$$\chi_{crit} = \chi_x 10^{-km}$$

which can be solved for k to yield

$$k = \frac{1}{m}\log_{10}\frac{\chi_x}{\chi_{crit}}$$

If $\chi_{crit} = \dfrac{\chi_x}{10}$

$$k = \frac{1}{m} = \frac{1}{(0.161 + 0.019U + 0.013\,\Delta T} \qquad (5\text{-}26)$$

I

It should be noted that, if a sampling interval different than 30 minutes were used, the constants in m would be different and k would still indicate the number of sampling intervals after release of FP. Equation (5-26) can also be used to obtain the time after drop for the concentration to fall to $\chi_x/10$. Thus the number of hours, n, after drop until $\chi = \chi_x/10$ is given by

$$n = 1 + \frac{1}{2(0.161 + 0.019U + 0.013\,\Delta T)} \qquad (5\text{-}27)$$

5.5.2 Recapitulation

The three operational equations that have been developed in this section are repeated here. Thirty minute sampling intervals are assumed.

1. Prediction of χ_x, the maximum ground-level concentration

$$\chi_x = 0.0176\,\sigma_\theta D_o \qquad (5\text{-}18)$$

2. Prediction of D_{gr}, the ground-level dosage

$$D_{gr} = 0.0216 + \frac{0.0176}{(10^{0.161 + 0.019U + 0.013\,\Delta T} - 1)}\,\sigma_\theta D_o$$

(5-24)

3. Prediction of n, the number of hours after drop until the ground-level concentration falls to $\chi_x/10$

$$n = 1 + \frac{1}{2(0.161 + 0.019U + 0.013\,\Delta T)} \qquad (5\text{-}27)$$

The four independent variables are defined as follows for prediction purposes. These are somewhat different than the original definitions because of the different context in which they will be used.

$\underline{\sigma_\theta}$

σ_θ is the standard deviation of the wind direction 50 ft above the top of the forest, at the time of effluent release, measured in degrees and determined with respect to 5-minute mean directions.

$\underline{D_o}$

D_o is the above canopy dosage resulting from the passage overhead of an instantaneous infinite, crosswind line source.

$\underline{U}$

U is the wind speed 50 ft above the top of the forest, averaged over the period beginning 1 hour after release and ending when ground level concentration returns to background. It is measured in mi/hr.

$\underline{\Delta T}$

ΔT is the 100-ft temperature minus the 6-ft temperature, measured in tenths of C degrees and averaged over the same period as specified for U.

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5.6 PREDICTION OF ABOVE-CANOPY DOSAGE

The prediction of absolute rather than relative ground level dosages clearly reduces to the prediction of above-canopy dosage. The following expression is given by Calder (4) for predicting dosage at the surface resulting from an elevated, instantaneous, infinite line source.

$$D_o(x) = \frac{2 Q_o e^{-h^2/2\sigma_z^2(x)}}{\sqrt{2\pi}\,\sigma_z(x)\,\bar{u}} \tag{5-28}$$

where

$D_o(x)$ = dosage at the surface at distance x from the source

Q_o = the strength of the source when released i. e. at $x = 0$

h = the height of the source above the surface

$\bar{u}$ = mean wind speed through the layer from the surface to the height of the source

$\sigma_z(x)$ = standard deviation of the vertical distance of particles from center of the cloud at x.

Equation (5-28) is a simplified form of the completely general Milly expression cited earlier.

Following the suggestion of Smith and Hay (5) we let

$$\sigma_z(x) = 3\,\sigma_\phi^2\,x$$

where

σ_ϕ = standard deviation of the wind inclination, averaged through the layer from the surface to the height of the source

x = distance from the source

and rewrite (5-28) as

$$D_o(x) = \sqrt{\frac{2}{\pi}} \frac{Q_o e^{-h^2/18\sigma_\phi^4 x^2}}{3\sigma_\phi^2 x \bar{u}} \tag{5-29}$$

Both (5-28) and (5-29) are based on the reflection principle which applies to diffusion over an impervious surface. Their applicability to diffusion over a forest surface, treating the top of the canopy as the zero plane, is in doubt in view of the substantial penetration of the forest that has been observed. It seems likely that a depletion of the original source cloud goes on as the cloud moves downwind over the forest, but some reflection is also likely from the top of the canopy. Moreover, only material reflected from the top of the canopy will remain with the original cloud whereas material reflected from the ground will emerge from the canopy long after the passage of the original cloud. Such a depletion process might be represented by replacing Q_o by a virtual source decaying exponentially with increasing distance downwind. If we denote Q as the virtual-source strength at any distance x from the original source we may write

$$dQ = -k\, f(W)\, Q\, dx$$

where k is a constant that is related to the effectiveness of the forest as a sink and f(W) is an unspecified function of weather that is a measure of the degree to which turbulence is penetrating the canopy. Integrating and setting $Q = Q_o$ at $x = 0$ gives

$$Q = Q_o e^{-Kf(W)x} \tag{5-30}$$

We observe from (5-30) that $Q = Q_o$ if $-kf(W)x = 0$, which is true when $x = 0$ (i.e., at the line of release), when $f(W) = 0$ (i.e., when turbulence is not penetrating the canopy), or when $k = 0$. The last case is the one of interest since $k = 0$ implies that the forest does not act as a sink. If it can be shown from the experimental data that $k>0$, direct evidence is provided that (5-30) describes the depletion of a plume in passing over a forest.

The procedure will consist of computing a mean value of k from the thirteen trials and then testing statistically the hypothesis that $k<0$. Rejection of the hypothesis will justify the form of equation (5-30). We proceed as follows. Introduce (5-30) into (5-29) and obtain

$$D_o(x) = \sqrt{\frac{2}{\pi}}\ \frac{Q_o \left[e^{-kf(W)x}\right]\left[e^{-h^2/18\,\sigma_\phi^4\,x^2}\right]}{3\,\sigma_\phi^2\,x\,\bar{u}} \tag{5-31}$$

The ratio between dosages at distances x_1 and x_2 downwind is then given by

$$\frac{D_o(x_1)}{D_o(x_2)} = \frac{x_2}{x_1}\, e^{kf(W)(x_2 - x_1)}\, e^{-\left[\frac{h^2(x_2 - x_1)}{18\,\sigma_\phi^4}\left(\frac{x_1 + x_2}{x_1^2\ x_2^2}\right)\right]} \tag{5-32}$$

It is shown in Section 5.4 that the standard deviation of wind direction, σ_θ, computed from the Beckman and Whitley vane on the north tower is a useful indicator of the degree of penetration by FP. Accordingly we let $f(W) = \sigma_\theta$. Although σ_ϕ was not measured at 200 ft it may be estimated from the expression

$$\sigma_\phi = \left(\frac{\sigma_w}{\sigma_v}\right)_{146\ \text{ft}} \sigma_\theta\ .$$

This assumes the same amount of non-isotropy in the turbulence at 146 and 200 ft. Equation 5-32 may now be solved for k in terms of known quantities to yield

$$k = \log_e \left\{ \left[\frac{D_o (x_1)}{D_o (x_2)} \right] + \frac{h^2 \quad (x_2 - x_1)}{18 \, \sigma_\phi^4} \left(\frac{x_1 + x_2}{x_1^2 \; x_2^2} \right) - \log_e \left[\frac{x_2}{x_1} \right] \right\} \cdot \sigma_\theta \, (x_2 - x_1) \tag{5-33}$$

It should be realized that the specific choice of f(W) determines the units for and introduces a scaling factor into k so that, we are really testing for the presence of a depletion effect on the line source, rather than evaluating k. The value of k is an index (of the retentiveness of this forest) relative to other forests only if the other determinations are made with the same specific form for f(W).

The data used in computing k are summarized in Table 5-3. Dosages were based on the two largest consecutive half-hourly counts in order to exclude delayed emanation from the forest. With the exception of trial 1, the three above-canopy measurements were combined at each tower to give a single value of $D_o (x_1)$. Lost rotorods at levels g and h in trial 1 have necessitated dosage determinations from level f (146 ft) alone. Trial 5 was not included because f-level counts were missing at station 12, and it is clear from the data that g- and h-level dosages are much greater than those at the f-level. Reasonable estimates of the missing f-level counts in trial 5 would lead to a large negative value of k implying the accretion of FP into the cloud, but it was shown in Section 3. 6. 1 that this apparent downwind increase was not statistically significant. For purposes of specifying h, the average height above ground of the undulating forest top was taken to be 130 ft, and the height of the source was taken from Table 3-1. The distances x_1 and x_2 were also obtained from Table 3-1.

The computed mean value of k is 24×10^{-4} deg^{-1} km^{-1}, which is not significantly different than zero. On the basis of these data there is no justification for rejecting Equation (5-28) in favor of (5-31) for predicting above-canopy dosage. Since it is known that some depletion is involved in the penetration that was observed, the results of this analysis imply that over the distances used in this study, losses due to depletion are small. The results cannot be considered the last word, however,

TABLE 5-3

VALUES OF THE KNOWN QUANTITIES IN EQUATION (5-33), AND COMPUTED VALUES OF k, BY TRIALS

Trial	$D_o(x_1)$	$D_o(x_2)$	h	x_1	x_2	σ_ϕ	σ_θ	$k \times 10^{-4}$
1	1701	1087	37 m	4.8 km	5.9 km	.38 ra	21 deg	104 $deg^{-1}\ km^{-1}$
2	3729	2752	21	3.2	4.3	.35	23	3
3	1131	1349	21	4.8	5.9	.42	23	-151
4	2080	2206	37	4.8	5.9	.09	15	-150
6	1712	1234	52	6.4	7.5	.21	17	90
7	1065	798	52	6.4	7.5	.12	17	72
8	752	772	52	6.4	7.5	.12	18	-91
9	6969	6759	52	1.6	2.7	.11	13	-162
10	12377	5667	52	1.6	2.7	.12	13	310
11	8155	7054	52	1.6	2.7	.11	12	-89
12	17326	9808	52	1.6	2.7	.22	18	31
13	7353	3179	52	4.8	5.9	.28	18	320

$\bar{k} = 24 \times 10^{-4}\ deg^{-1}\ km^{-1}$

"t" = 0.50 is not significant

because the distance between towers was too small in relation to the distance from the source to investigate this effect thoroughly. Moreover, the second term in the numerator of (5-33), - the critical term since it assesses the interplay of plume spread on the geometry of the problem, is subject to error. This is because of the inherent difficulties of precise location of the aircraft in the absence of visible ground fixes and the lack of a direct measurement of σ_{ϕ} at 200 ft. The possible role of plume depletion should be the subject of separate investigation employing an experimental design embodying the required sensitivity.

It is of interest to compare the actual dosages above canopy with those computed using equation (5-28). It will be assumed that the efficiency of the rotorod samplers is 50 percent and the efficiency of the FP dispenser is 35 percent.

Although a similar dispenser flown on an L-23 at 150 mi/hr was calibrated at 35 percent efficiency, the installation of the Aerocommander has not been calibrated. The comparisons are made for the first 90 minutes after FP release to eliminate the influence of emanations from the forest. The results are presented in Table 5-4.

The average of twelve trials indicates that observed dosages are 3.4 times the computed dosages. Since the only factors peculiar to this environment should decrease rather than increase the dosage, it is probable that the efficiency of the disseminator and rotorod samplers are greater than was assumed by this amount. The ratio between computed and observed dosage is relatively stable, which further supports the use of the existing diffusion formula for above-canopy predictions.

5.7 TESTING THE MODEL

A valid test of the model would require the collection of an independent set of data and the prediction of dosage and decrease times from the relationships developed here. This type of testing is impossible at this time. The best that one can do is assess the ability of the model to account for what happened in this field program.

Accordingly, values of the four independent variables were tabulated for each of the thirteen trials, the three operational equations of Section 5.5.2 were applied, and the estimates compared with the observed values. Table 5-5 presents these data and the correlation coefficients between observed and estimated values.

TABLE 5-4

OBSERVED ABOVE-CANOPY DOSAGES COMPARED TO DOSAGES COMPUTED FROM EQUATION (5-28)

Trial Number	Observed			Computed				Computed / Observed
	Station 1	Station 12	Mean	Station 1	Station 6	Station 12	Mean	
1	1701	1087	1394	124	110	99	111	.080
2	3729	2752	3240	533	451	391	458	.141
3	1131	1349	1240	908	775	627	770	.621
4	2080	2206	2143	1241	1119	1018	1126	.525
5	Msg	Msg	Msg	3693	3376	3016	3362	Msg
6	1712	1234	1473	354	323	297	325	.221
7	1065	798	932	320	293	270	294	.315
8	752	772	762	146	133	123	134	.176
9	6969	6759	6864	2699	1993	1577	2090	.304
10	12377	5667	9022	3742	3114	2594	3150	.349
11	8155	7054	7604	1699	1242	978	1306	.172
12	17326	9808	13567	4547	3395	2698	3547	.261
13	7353	3179	5266	1935	1737	1574	1749	.332

Mean = .291

TABLE 5-5

ESTIMATES AND OBSERVED VALUES OF χ_x, D_{gr}, AND n COMPARED FOR THIRTEEN TRIALS

(See page 5-20 for definitions of predictors)

Trial	D_o	σ_θ	U	ΔT	χ_x Obs.	χ_x Est.	D_{gr} Obs.	D_{gr} Est.	n Obs.	n Est.
1	1504	21	14	17	727	556	1027	845	1.5	1.8
2	3325	23	13	14	760	1346	1019	2105	2.0	1.8
3	1231	23	10	15	528	498	919	810	2.0	1.9
4	2093	15	10	5	524	552	1262	1020	3.0	2.2
5	7310	6	6	-2	533	771	1796	1955	4.5	3.0
6	1478	17	12	7	264	442	571	760	2.5	2.0
7	935	17	11	2	299	280	605	530	2.0	2.3
8	762	18	13	0	255	241	395	450	2.0	2.2
9	6648	13	4	-2	3101	1521	7389	4310	3.5	3.4
10	9022	13	9	4	1931	2064	3398	3990	2.5	2.3
11	7604	12	5	-2	1860	1606	5654	4270	3.5	3.2
12	13199	18	3	8	3328	4181	6582	8950	2.5	2.6
13	5266	18	9	3	1414	1668	2581	3280	2.5	2.3
					r^2 = 0.7410		0.7481		0.6738	
					r = 0.86		0.86		0.82	

A critical examination of Table 5-5 indicates that the poorest dosage estimates are for trials 2, 9, and 12. Trial 2 represents a 100 percent overestimate which results from an overestimate of χ_x. The overestimate can be traced to the failure of σ_θ to represent turbulence in the 50-ft layer above the canopy. Observers at the scene during this test noticed rapid movement of low scud from the north in the 2 hours before release of the FP, but it was only in the half hour before the drop that the 200-ft wind began to pick up. It appears that the turbulent transfer of momentum had not penetrated to the tree tops at the time of the drop for the 200 ft and 146 ft winds were 10 mi/hr and 2.6 mi/hr during intervals 5 and 6. This is almost a 4 to 1 ratio compared to 2 to 1 for day trials 1 and 3 undertaken three days before and after trial 2.

Trial 9 is unaccountable in terms of meteorology. Despite extremely light winds and only average turbulence, the penetration of FP as indicated by χ_x was exceptionally heavy. The observed persistence was compatible with the meteorological conditions but the underestimate of χ_x leads to a substantial underestimate of dosage.

Trial 12 is a case of overestimated dosage due mostly to an overestimate of χ_x. The overestimate is 35 percent, 25 percent due to overestimating χ_x and 10 percent due to overestimating the decline portion of the dosage. Trial 12 was a cloudy-day trial characterized by very light winds (3 mi/hr), moderately large σ_θ, and much less thermal turbulence than the other day trials, 1, 2, and 3. Evidently a large value of σ_θ overestimates the turbulence during light winds.

Another variable, U sin σ_θ was tried as an alternative to σ_θ as a predictor of the penetration ratio R. The correlation coefficient for the thirteen trials was only 0.39, compared to 0.53 when σ_θ was used, but even the latter value is disappointing. It must be conceded that the biggest area for improvement in the model is in the prediction of R. In future work of this kind, it is hoped to have reliable values of the ratio of wind speeds just above and 50 ft above the canopy, and a greater number of data points so that a second predictor of R may be considered.

If the presence of the trees is neglected for the moment and Milly's expression is used to compute ground level dosages some interesting results are obtained. Table 5-6 presents a comparison of these computations with the observed mean ground level dosages. Efficiencies of 35

TABLE 5-6

COMPARISON OF OBSERVED AND COMPUTED GROUND LEVEL DOSAGES
(COMPUTED VALUES ARE THOSE THAT WOULD OCCUR IF
THE TREES WERE ABSENT)

Trial	Observed Mean Dosage	Computed Mean Dosage If No Forest		Adjusted / Observed
		Assumed Eff. 35% to 50%	Adjusted	
1	1027	126	428	0.42
2	1019	439	1493	1.47
3	919	661	2247	2.44
4	1262	1296	4406	3.49
5	1796	3137	10666	5.94
6	571	295	1003	1.76
7	605	350	1190	1.97
8	395	136	462	1.17
9	7389	2490	8466	1.15
10	3398	2048	6963	2.05
11	5654	1288	4379	0.77
12	6582	3531	12005	1.82
13	2581	1736	5905	2.29
			Mean =	2.06

and 50 percent were assumed for the disseminator and rotorod samplers. Recalling that similar above-canopy computations in Section 5.6 indicate that actual efficiencies appear to be 3.4 times greater, all of the computed values were adjusted by the factor 3.4 and the ratio "adjusted/observed" was computed. A mean value of 2.06 is obtained but there is considerable scatter of the points.

Not only would the Milly expression overestimate dosages by a factor of about two, but it predicts high concentrations of short duration rather than the low concentrations of much greater duration which actually occur. Some idea of the magnitude of this factor is readily computed.

The Bendix model shows that the duration of a fumigation up until the concentration falls to $\chi_{max}/10$ is given by

$$\text{Duration} = 1 + \frac{1}{2m} \text{ hours}$$

where $m = 0.161 + 0.019\ U + 0.013\ \Delta T$. The Milly model predicts the duration between $\chi_{max}/10$ points on the concentration versus time curve as

$$\text{Duration} = \frac{4.3\ \sigma_x}{\bar{u}}$$

where σ_x and $\bar{u}$ are averaged from surface to the axis of the cloud.

If $\sigma_x = \sigma_y = \sigma_\theta x$,

$$\text{Duration} = \frac{4.3\ \sigma_\theta x}{\bar{u}}$$

Letting U_{200} = 10 mi/hr, ΔT = 5 tenths C°, σ_θ = .35 radians, $\bar{u}$ = 240 m/min., the Bendix model shows that the duration of the fumigation under the trees is 127 minutes whereas the diffusion model assumes a 30-minute duration. Combing this factor with the overestimate of dosage, it appears that actual concentrations under the forest are about 1/8 of what would occur if the trees were not there.

5.8 APPLICABILITY AND LIMITATIONS OF THE MODEL

The model in its present form applies specifically to the forest in which the data were collected. It seems reasonable to assume that the

behavior of the FP tracer was influenced by the height of the forest and the vegetative density. In fact, both quantities were considered in the theoretical development of the model. Although no attempt was made at developing an index of forest density, the very complete survey of the forest contained in Volume II of this report would permit the development of such an index. A complete generalization of the model requires the collection of comparable data in dissimilar forests whose physical descriptions are equally well documented.

Pending the collection of such data some general guidance is needed for the use of this model at other sites. Since the forest at the study site was exceptionally high and uniformly free of large holes it is probable that the penetration would be greater at most other sites. Accordingly, it is suggested that for most other sites dosage predictions based on the present model would underestimate the true dosage, which is the preferred sign for the error. If the forest at the other site is known to be taller than 150 ft, dosage predictions should be scaled down somewhat.

The model assumes 30-minute sampling intervals as a result of which the predicted value of χ_x represents an average over a 30-minute interval. It is, in fact, the total dosage during the 30 minutes of highest average concentration, rather than strictly a concentration. The assumption of 30-minute sampling intervals in no way restricts the applicability of the equations for predicting dosage or persistence. If, for example, a 15-minute sampling interval had been used, compensating changes would have occurred in the constant coefficients of the two fundamental prediction equations

$$\hat{R} = 0.0176\ \sigma_\theta \tag{5-11}$$

and

$$\log_{10}\left(\frac{\chi_{x+i}}{\chi_{x+i+1}}\right) = 0.161 + 0.019U + 0.013\ \Delta T \tag{5-16}$$

As a result the new equation for χ_x (see Equation 5-18) would have referred to the maximum 15-minute dosage, and the new equation for persistence (see Equation 5-26) would have given the number of 15-minute intervals until the concentration fell to $\frac{\chi_x}{10}$.

Two of the three meteorological predictors, σ_θ and ΔT are quantities that are marginally standard and not part of the forecaster's standard repertoire. For this reason, and because it is more easily measured and probably more relevant, future work should attempt to replace σ_θ with $U_h / U_{h + 50}$ where U_h is the wind speed at the top of the forest and $U_{h + 50}$ is the wind speed 50 ft above the forest. ΔT was admittedly a stop-gap to replace the lapse rate above the canopy.

Future work should aim at replacing ΔT with measurements of above-canopy lapse rate since this is the prime quantity in the theoretical model and since it is generally predictable.

SECTION 6

THE ROLE OF GRAVITATIONAL SETTLING

Early in the analysis of the data it became evident that the mechanism of turbulent diffusion could account for the main features of penetration and decay. From that point on, the analysis, as reflected in the preceding sections of this report, emphasized the role of meteorological factors and minimized gravitational settling on the grounds that its influence was negligibly small. Since settling does appear in the model of Section 5 as one of the factors contributing to the decrease of FP concentration, it is appropriate to review here all the evidence for minimizing the role of settling.

At the outset it may be assumed that gravitational settling of the FP tracer was in accordance with Stokes' Law. This means that the assumed settling rate is 2.74 meters/hr or approximately 9 ft/hr as given in Section 2, With this as a ground rule, the evidence for minimizing settling is presented, and the implications of observed losses due to settling are examined.

6.1 BASIS FOR MINIMIZING THE ROLE OF SETTLING

If settling were the dominant mechanism, certain patterns would emerge in the data. Hence the evidence listed below involves the comparison of expectation with observation.

1. As pointed out in Section 4, settling cannot account for the early appearance of FP at the 6.5 ft level. In trial 12 it is estimated that the line source took 20 minutes to reach the array so that it reached 6.5 ft within 10 minutes of its arrival overhead at a height of 150 ft. Settling can account for about 1.5 ft of descent in 10 minutes, but the rest of the 150 ft must be attributed to turbulent mixing. If, instead of the initial appearance of FP, we consider the arrival of the main portion, we observe that the maximum concentration at 6.5 ft lags the maximum above the canopy by only 30 minutes. In 30 minutes gravitational settling would account for only 4.5 ft of descent. It follows that gravitational settling may be ignored in explaining the initial penetration of the forest by FP.

2. If the decrease of FP concentration within the forest were due primarily to settling, the time for concentration to return to zero would be the same for all trials. In fact, there is considerable variability, from 1 hour in trial 1 to 6 hours in trials 9 and 11.

3. When the decrease is attributed to turbulent mixing, the observed variability in the time for decrease is well accounted for by variations in meteorological factors.

4. If settling were the major factor in the disappearance of FP, the gradient of concentration would remain directed downward in the lower layers as it was at the onset of the fumigation. Examination of Figures 3-1, 3-2, and 3-3 shows that, with the exception of trials 5, 9, and 11 the gradient is directed upward throughout the period of decreasing concentration (i.e., after interval 6).

5. If settling were the major process occurring within the forest, the FP would sink steadily into the forest, disappearing first from the top of the forest and then in progression at heights nearer the ground. In fact, the FP remains above background levels at all heights even up to 50 ft above the canopy as long as it is present at the bottom of the forest.

For the five reasons just cited, it is concluded that settling plays a negligible role in the initial fumigation, and in the majority of cases a negligible role in the disappearance of FP from within the forest.

6.2 QUANTITATIVE ESTIMATES OF SETTLING BASED ON THE MODEL OF SECTION 5

It is shown in Section 5, Equation (5-26), that the ground level concentration decays to 1/10 of its maximum value in 1/2 m hours or to 1/100 in 1/m hours where

$$m = 0.161 + 0.019U + 0.013\,\Delta T$$

The last two terms on the right hand side represent the meteorological contribution to decay, and as was shown in the argument preceding the derivation of Equation (5-13) in Section 5.4.2, the quantity 0.161 is a

measure of losses due to settling. Two cases of special interest are:

Case 1 $\qquad 0.161 << 0.019\ U + 0.013\ \Delta T$

Case 2 $\qquad 0.161 >> 0.019\ U + 0.013\ \Delta T$

Case 1 may be identified as that in which the influence of settling is negligible, and Case 2 as that in which the influence of settling is more important than turbulent diffusion, in the decrease of concentration.

Reference to Table 5-5 for values of U and ΔT shows that trials 1, 2, 3, and 6 are good examples of case 1 ($0.019\ U + 0.013\ \Delta T = 0.487$, 0.429, 0.385, and 0.319). Examination of Figures 3-1, and 3-2 shows that in each of these trials the successive profiles of concentration versus height are as expected when the influence of settling is so small as to be masked by turbulent diffusion. Table 5-5 also shows that trials 5, 9, and 11 are good examples of case 2 ($0.019\ U + 0.013\ \Delta T = 0.088$, 0.050, and 0.069). Examination of Figures 3-1, 3-2, and 3-3 does, in fact, show the downward directed gradient in the lowest layers (referred to in item 4 of Section 6.1) which must characterize the profiles when settling is the dominant factor.

It is concluded that the role of gravitational settling is negligible most of the time, but under exceptionally stagnant meteorological conditions settling may be important. The model developed in Section 5 appears to depict, with reasonable accuracy, the relative roles of settling and turbulent diffusion in the decrease of FP concentration within the forest.

From the model of Section 5, some inferences may be drawn concerning the interception of settling particles by vegetation. Suppose that the meteorological contribution to decay is zero. Then the time required for the concentration to decay to 1/100 of its maximum is 6.2 hours. Since the FP tracer settles at a rate of 9 ft/hr it follows that particles present after 6.2 hours have settled through a 56-ft layer, and conversely, particles at higher elevations have been almost completely removed by settling on the vegetation.

The interception of settling particles by the vegetation may be expressed analytically in the following way. We consider some reference plane above ground from which we measure positively downward. Let n be the number of particles in a thin slice of air of a unit volume at distance

z below the reference plane. The number of particles, dn, lost on vegetation in settling through a distance dz is given by

$$dn = -kn\, dz$$

where k is a constant which measures the impermeability of the forest to settling particles. By integrating and setting $n = n_o$ at the reference plane, we obtain, as an expression for the number of particles remaining in a unit volume, after settling, at any distance z below the reference plane

$$n/n_o = e^{-kz} \tag{6-1}$$

During trials 5, 9, and 11, when settling was apparently important, the particle counts were relatively uniform through the lowest 75 ft so that n_o is also representative of the number of particles at 6.5 ft. We have already computed that settling through 56 ft reduces the particle count to 1/100 of its maximum. Therefore if we set $n/n_o = 0.01$, and $z = 56$ ft in Equation (6-1), we obtain $k = 0.082\ \text{ft}^{-1}$. We note that k refers to the lowest 56 ft of forest.

Qualitatively, the above discussion shows that losses of FP due to settling occur not only at the ground, but also on the foliage. Quantitatively the evaluation of k implies that about 8 percent of the settling fluorescent particles are lost in passing down through each foot of this forest. No doubt k is a measure of the density of the vegetation below the canopy, and may vary from one forest to another. It may be shown that the preceding argument leads also to the following general expression for k for any forest:

$$k = 4.6\, b_o/V_s \tag{6-2}$$

where 4.6 is $\log_e 100$, b_o is the regression constant first introduced in Equation (5-15) (0.161 for the current study), and V_s is the settling speed of the aerosol being used. Equation (6-2) tells us that the less dense the forest, the less important will settling be to decay, since b_o is related directly to k.

SECTION 7

CONCLUSIONS

The following conclusions are responsive to the four program objectives cited in Section 1 of this volume. These concise statements are referenced to earlier portions of this volume for more complete discussions.

1. The diffusive processes in the region just above and below the canopy, following the cross wind release of an "instantaneous, infinite" line source result in the creation, within the forest, of an extensive volume source. The initial strength of this source is determined by the strength of the primary source, by the degree of turbulence at the time of release, by the density of the forest, and by other unidentified factors. The rate of decrease of this source is directly proportional to the wind speed and lapse rate above the canopy since these factors are primarily responsible for the removal of the material. Sections 4 and 5 elaborate on these ideas.

2. The distribution of tracer material below the canopy is a function of time. During the first half hour after release of the tracer a strong, downward-directed gradient is observed. With the rapid movement downwind of the source cloud and the commencement of tracer losses at the top of the forest, the gradient quickly reverses and is directed upward thereafter until the tracer concentration returns to background levels. Background remained at zero throughout the series of 13 trials. The usual result of these conflicting concentration gradients, over the duration of the fumigation, is decreasing dosage with increasing distance below the canopy. Further details appear in Sections 3.2 and 3.7.

3. Above the canopy, the cloud from the primary line source moves along downwind at the speed of the wind at cloud level. Below the canopy, and in particular at ground level, the secondary volume source is, for practical purposes, at rest. The very slight advection of the material, as described in Section 3-4, plays an insignificant role in its eventual disappearance.

4. A diffusion model has been developed for the prediction of ground level dosage (see Section 5-5) using wind and temperature data as predictors. Predictions are also described for the maximum ground level concentration and the time required for concentration to decay to one tenth of its maximum.

In addition, the following conclusions appear warranted on the basis of Sections 5.6 and 6.

5. Above-canopy dosage can be predicted with sufficient accuracy by models which treat the top of the forest as an impervious surface, although a suggestion of source attenuation was noted.

6. With regard to gravitational settling, it is concluded that settling plays a negligible role in the initial fumigation, and in the majority of cases a negligible role in the disappearance of FP from within the forest. The model developed in Section 5 depicts the relative roles of settling and turbulent diffusion in the decrease of FP within the forest. A complete discussion of settling appears in Section 6.

7. Concentrations of FP at ground level are approximately 1/8 of those that would occur if the trees were not present.

SECTION 8

RECOMMENDATIONS

The following recommendations derive logically from the work described in this report. They are divided into those which constitute improvements to experimental design for investigating penetration of a forest and those which constitute extensions to the scope of the present study.

8.1 RECOMMENDATIONS PERTAINING TO EXPERIMENTAL DESIGN

1. A standard sampling interval of 15 minutes should be adopted in preference to 30 minutes in order to provide better time definition of the fumigation.

2. Monitoring of the background for 30 minutes prior to release of a tracer is recommended as entirely adequate and therefore preferred to the 120 minutes used in this study.

3. The duration of trials should be reduced consistent with the expected rate of disappearance of the tracer. Sampling should be discontinued when the concentration is expected to fall below 1 percent of the ground level maximum. Two iterations of Equation (5-26) give the following average results:

Daytime	Discontinue sampling 3 hours after release
Nighttime, wind $\geq$ 8 mi/hr	Discontinue sampling 4 hours after release
Nighttime, wind < 5 mi/hr	Discontinue sampling 7 hours after release

4. Development should be undertaken of a new sensor for measuring air movements in environments where extremely light winds and dew or rain are frequent. In a tropical rainforest where dew is present over 50 percent of the time, the anemometer bivane readily becomes tail heavy and ceases to function.

5. Some direct measurement should be made of the downward transport of momentum in the 50 feet directly above the canopy. This may be accomplished by the measurement of wind speed at the top of the canopy and 50 feet above the canopy, U_h and U_{h+50}, respectively. The possibility of using the ratio U_h/U_{h+50} in preference to σ_θ, as a predictor of the penetration ratio, R, should then be fully evaluated.

6. The lapse rate in the first few hundred feet above the canopy should be measured and its effect on the decrease of concentration determined. Moreover, the apparent relationship between the above canopy lapse rate and that below the canopy should be the subject of direct investigation since it is generally simpler to measure the lapse rate below the canopy than in the first few hundred feet above the canopy.

8.2 RECOMMENDATIONS PERTAINING TO INCREASED SCOPE

The investigation of penetration described herein was carried out with the simplest possible boundary conditions, namely the forest was situated on level ground, the forest was extensive and devoid of holes, and the trials were carried out in the absence of rain. Since it is exceptional to encounter such ideal conditions, it is important to learn how the present results are modified by the introduction of different boundary conditions. The following recommendations are directed towards acquiring this knowledge.

1. Penetration through forests situated on hilly ground should be investigated.

2. Penetration through forests of limited extent, characterized by occasional holes, should be investigated.

3. The investigation into effects caused by hills and valleys, and by holes in the forest should be combined into a single field experiment using a design based on analysis of variance techniques, in order to effect a saving in time and money. Suitable forests for this type of study are found in Eastern United States, for example.

4. Some future penetration studies should be carried out during rain to investigate the influence of rain at the time of release of tracer and rain that begins soon after the release. In essence, this involves studying separately the influence of rain on the primary source above the forest and on the secondary source within the forest.

5. A field experiment should be carried out to investigate the possible attenuation of source clouds in passing over forests for distances of the order of 5 to 50 miles. The discussion in Section 5.6 might serve as a basis for the test plan.

SECTION 9

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An investigation of rainforest ventilation in northwestern Colombia is described in 3 volumes. 13 trials were conducted of the diffusion of a fluorescent tracer. Concurrent meteorological and vegetation studies were performed. Volume I describes the diffusion measurements, Volume II the vegetation and meteorological studies and Volume III the logistics, instrumentation, and data processing aspects of the investigation.

The diffusion measurements described in this volume were made by rotorod samplers at 65 points on towers and trees in the forest. Rotorods were changed every 30 min during trials. The results suggest the following mechanism of penetration and diffusion. A portion of the tracer cloud passing overhead penetrates the canopy where it becomes an extensive, relatively persistent secondary source. The depletion of this source is attributed primarily to turbulent flux upward through the canopy. Gravitational settling and advection play minor roles. A mathematical model of the processes is developed using wind and temperature data as predictors. The model is evaluated and recommendations are given for future work.

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